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Abstract

In order to characterize the nature and significance of solifluction mass wasting within the Alberta portion of the Canadian Rocky Mountains 58 turf-banked solifluction lobes underwent geomorphological examination and process monitoring between 1980 and 1983. The objective of this research was to document the rate of contemporary solifluction, to establish its biophysical and environmental controls, and to characterize its historical rate of activity in this region.

Morphological evidence of solifluction was abundant within the Alberta Rocky Mountains, with turf-banked solifluction lobes representing perhaps the dominant expression. The results of a spatial inventory indicated that solifluction lobes were found on moderately steep alpine tundra slopes (18° ± 6.8°) located within a very narrow altitudinal belt (200 m in width) immediately above the local treeline. Morphometric analysis disclosed that a typical lobe form in this area had a tread angle of 21° ± 8.1°, a riser height of 0.41 m ± 0.16 m, a tread length of 2.56 m ± 1.89 m, and a tread width of 3.88 m ± 2.19 m. Textural analysis of the sediments contained within these lobes disclosed they consisted of a highly frost susceptible silty to stony loam having low liquid limits and limited plasticity.

Soil movements at the 58 study lobes were measured using plastic inclinometer tubes, wooden dowel pillars and networks of painted stones. These measurements yielded 447 plot-years of surface movement data at 185 points and 126 plot-years of volumetric transport data at 44 different points. Most of this downslope movement was confined to the upper 30 to 35 cm of sediment, where the average rate of movement ranged from zero to 2.50 cm/year at the ground surface. Based on the establishment of normal distributions within the pooled data, it was estimated that the mean rate of solifluction transport within the field area was 0.62 ± 0.21 cm/year and that approximately 8.67 ± 3.57 cm^3/cm of sediment was moved annually by solifluction. Significantly, these rates of activity were shown to vary only slightly in the field area over the study period.

Frost heave bedstead measurements made at two high altitude sites described average seasonal frost heave values ranging from 2.3 to 4.5 cm/yr. When compared to the solifluction movement data, these results emphasized the large contribution made by frost creep mechanisms to solifluction in this area. Exceptions were noted, but these were localized and attributed to gelifluction flows occurring under particularly favourable conditions.

The rate of solifluction transport was strongly correlated to its spatial setting, with the highest rates of movement recorded on steeply dipping north- to northeast-facing slopes. Seasonal microclimatic fluctuations appeared to result in temporal fluctuations in the local rate of solifluction. Conversely, solifluction transport rates were not shown to differ significantly with regards to variations in the contained solifluction sediments or with variations in the character of the covering mantle of vegetation.

Radiocarbon records from beneath two solifluction lobes demonstrated that solifluction processes had been continuously active, although at varying rates, for at least the last 4000 years in this area. Comparison with the local paleoclimatic record suggested that these rate changes were probably a result of historical climatic fluctuations.

The results of this research program bear witness to the contemporary geomorphic significance of solifluction activity within the Alberta Rocky Mountains. Even though its morphological effects are, at best, only subtly manifest, solifluction accomplishes an amount of geomorphic work which ranks in importance close to many other slope processes active in this high mountain setting.

Acknowledgements

The field investigations described in this dissertation would not have been attempted without the support of the Boreal Institute for Northern Studies at the University of Alberta. Through a series of Grants-in-Aid between 1980 and 1983, the Institute provided the funding necessary to ensure the successful completion of this research program. Special thanks are due to the members of the Institute who recognized the value of this project, even though its focus was somewhat outside the traditional Boreal mandate. Thanks are also due to the staff of the Boreal Institute who played no small role in ensuring the logistical success of the project.

I am deeply indebted to Dr. H.J. McPherson my thesis supervisor for, first of all, his advice and critical appraisal at all stages of this project, and secondly, for his friendship during my association with the University of Alberta. I would also like to express my thanks to my examination committee who guided the dissertation through its final stages.

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Appreciation is also extended to the Geography Department at the University of Alberta and to the Kananaskis Centre for Environmental Research who provided varied logistical support over the research period. In the case of the Kananaskis Centre, I wish to extend a special vote of thanks for accepting me as part of their extended community.

The spatial scope of this project necessitated obtaining permission to do research in three separate areas of the Alberta Rockies. Alberta Recreation and Parks kindly granted permission to work in Kananaskis Provincial Park and in the adjoining Kananaskis Country. R.H. Swanson at the Northern Forest Research Centre provided the opportunity to do research in the Marmot Creek Experimental Basin beneath Mt.Allan, where the cooperation of Z.Fisera was always forthcoming. Finally, Parks Canada and the chief warden of Banff National Park permitted the monitoring of solifluction activity at Parkers Ridge. To all of these people and agencies, I extend my thanks.

In all, four summers were spent in the field gathering the data for this study. Over that time period a number of colleagues and friends contributed to this study in one way or another. To Jamie Steel, who was my field assistant in 1980, I'd like to extend my sincere thanks. I'd also like to extend my appreciation to the rest of the Waterloo crew, including Sally Drewery, Norm Jones, Mary Sauchyn and Dave Sauchyn, who lived in the 'gravel pit' with me and helped in many different ways. To the others, including my sister, who came to holiday and were put to 'work', I extend my sincere thanks.

The winter fieldwork carried out in Kananaskis Provincial Park had its own special problems and dangers. However, thanks to the support and encouragement provided by chief park ranger Jim Murphy, these were usually overcome or at least minimized. To the various park wardens and employees who accompanied me on my sojurns to Highwood Summit and above, I extend a special vote of thanks. In particular, I'd like to thank B.Duncan, D.Hanna and G.Harrison who seemed to be drafted more often than not. I am also grateful to Don Jennings, who accompanied me on several of these mid-winter trips to Kananaskis.

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1. INTRODUCTION

1.1 Purpose of the Research

Mass movement processes are an important element of geomorphic change in mountain landscapes. Where alpine slopes are steep, high levels of gravitational stress promote rapid, often catastrophic movements (Hewitt, 1972; Gardner, 1979a). The resulting landforms are among the most striking of the high alpine and considerable effort has been devoted to understanding their activity (c.f. Whalley, 1974; Hungr, 1981). Far less attention has been paid to the subtle geomorphic changes which occur on less steeply sloping segments of the alpine. Because slope processes in these lower energy enclaves operate on a more continuous basis, they ultimately perform large amounts of geomorphic work (Caine, 1976a; Barsch and Caine, 1984). Nevertheless, in most high mountain landscapes little is known about these slow mass movement processes.

The purpose of this research was to establish the character of slow mass wasting in high alpine landscapes of the Canadian Rocky Mountains of western Canada. Previous attempts had done little to reveal the dynamics of many of the slow mass processes which are known to be active in this region, despite varied morphological evidence of their activity (c.f. Slaymaker and McPherson, 1977; Luckman, 1981). Solifluction is, almost certainly, one of the most important of these processes. It describes a particular type of slow flow-like soil movement resulting from the combined action of a suite of periglacial processes (C.Harris, 1981a). Because the relative importance of each interacting mechanism varies both spatially and temporally (Jahn, 1975), the landforms produced by solifluction take many forms (Embleton and King, 1975; French, 1976; Washburn, 1979). Among the most striking, especially in the high alpine (c.f. Graf, 1971, 1973), are tongue-shaped solifluction lobes. By focusing the objectives of this study solely on the activity of solifluction lobes, the morphodynamic nature of solifluction processes within this region was clearly evaluated.

1.2 Objectives of the Research

The three main objectives of this study, listed in order of priority, were:

1. To document the rate and character of contemporary solifluction lobe movements.
2. To evaluate the geomorphological and environmental parameters which influence contemporary solifluction lobe movements.
3. To document the rate and character of historical solifluction lobe activity.

The aim of Objective 1 was to establish the character of solifluction processes in the Canadian Rockies. As a result, considerable effort was devoted to monitoring solifluction activity at a number of locations over several years. Since the factors which control solifluction are multiple and difficult to quantify, Objective 2 concentrated upon assessing the impact several key geomorphological and environmental parameters had on local solifluction activity. Overall these objectives served to characterize the morphodynamic nature of present-day solifluction in this region and to indicate its relative significance.

Objective 3 was designed to illustrate the character of historical solifluction behavior. While limited resources restricted the attention paid to this objective, sufficient data were collected to provide some insight into past solifluction activity.

1.3 Methodology of the Research

The field work undertaken for this project focused on establishing the characteristics of solifluction mass wasting occurring at turf-banked solifluction lobe sites. This research was completed within representative areas of the Alberta Rocky Mountains. Investigations of **contemporary** movements were made using a variety of instruments and sampling techniques. The *rate* of this activity was measured using an assemblage of methods which included the use of inclinometer tubes, dowel pillars and painted stones. The *mechanisms* involved in this activity were evaluated using frost heave bedsteads and a research program that involved intensive displacement monitoring within limited areas. The *environmental controls* influencing present-day activity were evaluated through a series of microclimatological studies completed within one of the study areas. The magnitude of historical solifluction activity within the field area was examined by radiocarbon dating samples of organic layers buried by the advance of two different lobes located within one of the study areas.

Overall, the period of this investigation extended from June 1980 to November 1983. Most of the data were collected during three summer field seasons (1980, 1981, 1982) when research was undertaken on a daily basis from early-June to late-September, and two winter field seasons (1980-1981, 1981-1982) when research was undertaken at monthly intervals. In 1983, the research program was completed during a series of short-term excursions.

1.4 Format of the Dissertation

This dissertation is composed of ten chapters plus appendices. Following this introductory chapter, Chapter 2 describes the process of solifluction and reviews the morphodynamic development of solifluction lobes. Included is a discussion of solifluction lobe activity in high mountain landscapes. Chapter 3 describes the Alberta Rocky Mountain field area and reviews what was previously known about the distribution and behavior of solifluction within this region. Chapter 4 outlines the environmental and biophysical characteristics of the study areas, and describes their geomorphological character. Chapter 5 presents the results of an investigation into the geomorphological context of the turf-banked solifluction lobes selected for monitoring. Chapter 6 discusses the rates of contemporary solifluction processes, as well as their spatial and temporal variability. In Chapter 7, the results of a series of experimental procedures designed to highlight the contributions made by the different solifluction mechanisms over the study period are reviewed. Chapter 8 discusses the links between a variety of geomorphic, climatologic and biologic parameters, and the rates of solifluction measured during this research program. In Chapter 9, the character of historical solifluction is examined, with specific reference to its environmental significance. In the concluding chapter, the results of this program are briefly summarized.

2. SOLIFLUCTION PROCESSES AND LOBES

2.1 Introduction

The purpose of this chapter is to review the morphogenesis of the solifluction process, which leads into a discussion of the morphodynamic behavior of solifluction lobes. Particular attention is given to establishing the character of solifluction lobes in mountainous settings where previous researchers describe distinctive morphoclimatic conditions (Benedict, 1976; C.Harris, 1981a).

2.2 The Solifluction Process

Solifluction is an established term which has been used to describe a distinct form of periglacial mass wasting. It was first utilized by Andersson (1906) to describe the process responsible for the flow-like motion of ***mud glaciers*** on Bear Island in the Arctic Ocean. While there has been considerable variation in the use of the term over the intervening years (Dylik, 1967; Washburn, 1967), it is still understood to characterize similar soil flows. Presently, the term **solifluction** is used to describe the slow downslope transfer of sediment resulting from the combined effect of **frost creep** and **gelifluction** mechanisms (French, 1976:135; C.Harris, 1981a:4). Implicit in the contemporary use of the term is the assumption that solifluction by definition is restricted to periglacial zones where intense freezing and thawing of the ground are essential elements of its motion (Karte and Liedtke, 1981).

2.2.1 Mechanisms of Solifluction

Solifluction is the product of gravity actuated mass movement. Field experimentation has repeatedly confirmed that two mechanisms, frost creep and gelifluction, largely determine its nature (Williams, 1966). Nonetheless, it is usually difficult to differentiate between the relative importance of either process since they commonly operate together (Benedict, 1970:170; Journaux, 1976:273).

The role of **frost creep** in this relationship is the most subtle. Frost creep describes the thaw settlement of frost heaved sediments (Davison, 1889; Washburn, 1979). **Frost heave** is caused by the growth of segregated ice lenses in a freezing soil (Konrad and Morgenstern, 1980), which results in horizontal soil bulking. On thawing, these frost heaved sediments resettle vertically downslope under the influence of gravity. Jahn (1975:145) has shown that **the potential frost creep** generated by this expansion and contraction motion is the product of the amount of frost heave and the local slope.

Downslope movements attributed to frost creep are generally small (Washburn, 1967; Owens, 1969; C.Harris, 1977). However, several investigators (Everett, 1967; Benedict, 1970; Jahn, 1976) have recorded large amounts of frost creep corresponding to locations of high pre-freeze soil moisture. In either case, the relative amount of frost creep always decreases rapidly with depth below the ground surface. As a consequence, frost creep is only rarely regarded as a significant component of solifluction (McRoberts and Morgenstern, 1974; McRoberts, 1978).

Perhaps a more important outcome of frost creep is the attendant decrease in slope stability. Typically, frost heave destroys soil aggregates (Bryan, 1971), increases void ratios (Konrad, 1980), and produces large discontinuities where soil particles are separated by ice lenses (Miller, 1972; Anderson and Morgenstern, 1973). Upon thawing, and until these soils consolidate, they commonly exhibit drastic losses in shear strength (Williams, 1957; C.Harris, 1977). In addition, melting of frost heaved soils results in high soil moisture values as the segregated ice lenses melt. If ground thaw proceeds at a sufficient rate, soil-water mixtures in this state are easily mobilized (c.f. Hutchinson, 1974). Consequently, frost heave may be more effective in the promotion of gelifluction than it is in the production of substantial frost creep. Evidently gelifluction is most effective when the soil has been preconditioned by frost heaving (Williams, 1959; Benedict, 1970).

Gelifluction describes the downslope flow of thawed sediments over a seasonally or permanently frozen subsurface (Baulig, 1957; Washburn, 1967). Significant movement occurs only during the principal thaw season when the uppermost layers become soaked with meltwater derived from snow and segregated ice lenses (Bird, 1967). In most cases deformation begins when soil-water exceeds the liquid limit and the soil grains are no longer in contact with each other (Washburn, 1967; C.Harris, 1977, 1981a). However, Fritze (1971) has stressed that saturated conditions alone do not ensure gelifluction.

The exact mechanism of gelifluction remains disputed (Carson and Kirkby, 1972; Washburn, 1979). It is usually assumed that saturating a soil substantially increases its weight while reducing its internal friction (Embleton and King, 1975; Brunsden, 1979). Presumably gelifluction commences when these elements, having attained some critical threshold, combine with gravitational stress. Unfortunately, the mechanics of gelifluction are not that easily resolved due to their polyphyletic nature.

Explanations of gelifluction include elements of both flow and sliding motion. Generally, gelifluction movement is thought to consist of a number of short lubricated flows along discrete planes (Carson and Kirkby, 1972). In essence, this motion results from short-term rheological failure associated with the downward migrating thaw plane. Under these circumstances losses in effective stress are caused either by artesian pressures (Weeks, 1969; Chandler, 1970, 1972); by ice-blocked drainage (Siple, 1952); by the rapid melting of segregated ice lenses (Beskow, 1935; Jahn, 1967; Hutchinson, 1974); or by thaw-consolidation under self weight conditions (McRoberts and Morgenstern, 1974; Nixon and Ladanyi, 1978). The end result is a near linear decrease in the magnitude of movement below the ground surface (Young, 1972).

Gelifluction may also occur as the result of block movements. In this instance relatively thick slabs of soil move downslope independently as rigid masses of sediment. Movement occurs along discrete shear planes caused by the loading of the thawing active layer (Zhigarev, 1967; Hutchinson and Bhandari, 1971). Failures of this type occur through transitional shearing (Jahn and Cielinska, 1974; Rampton and Dugal, 1974) or basal sliding (Jahn, 1967; Mackay, 1981; Reanier and Ugolini, 1983). Often the failure surfaces are delineated by strong textural differences (Jahn 1979a, 1979b) or abrupt changes in soil moisture caused by soil freezing (Rein and Burrous, 1980; Mackay, 1981). This process results in conspicuous plug-like flows where the different layers are separated by shear/slip surfaces.

Alternatively, gelifluction may involve relatively wet masses of soil in a type of viscous flow. Vallejo (1980) and Mackay (1981) recognized that following the rapid thaw of frost heaved ground many sediments temporarily consist of a mixture of soil particles, residual ice lenses, and a liquid-like soil slurry matrix. According to Bagnold (1956) soil in this disturbed state is easily mobilized. Motion can, for instance, be initiated as soil grains propelled by gravity collide with one another (Brunsden, 1979:143). This effectively reduces the normal dispersive stresses, causing a fluid-like motion (Vliet-Lanoe, 1983). Movements attributed to this form of gelifluction are relatively rapid, although of limited duration.

Assessment of the relative contribution of frost creep and gelifluction to solifluction is complicated by a number of factors. Spatial and temporal overlaps make it difficult to differentiate between the singular effect of either. Benedict (1970), for example, has indicated that the importance of either mechanism varies from year to year and site to site. As a general rule though, frost creep tends to be more important on drier slopes, whereas gelifluction predominates on wetter, well-vegetated slopes. Still the lack of a sharp distinction between the two mechanisms means it is often better to consider their combined effect as solifluction.

Both mechanisms suffer losses due to **retrograde movements** which diminish potential motion. Retrograde, or upslope, displacements reflect the tendency for soil to settle normal to the slope. The mechanisms responsible have proven difficult to evaluate, although capillary pressures (Washburn, 1967), interparticle cohesion (Ahnert, 1971), desiccation (Kojan, 1967; Rein and Burrous, 1980), and cracks (Young, 1960) or fissures (Fleming and Johnson, 1975) all seem to cause upslope shrinkage at an angle between the vertical and the perpendicular (Young, 1972:50). Field studies have demonstrated that retrograde movements reduce the effect of solifluction by anywhere from 10 to 50 percent (c.f. Washburn, 1967).

Solifluction is also indirectly influenced by the operation of a number of other geomorphic processes. For example, continuous soil creep almost certainly contributes, if only to a minor extent, to solifluction movements (Price, 1981). Additional, often ambiguous contributions to solifluction result from soil movements prompted by aeolian activity (White and Mottershead, 1969; Jahn, 1972; Troll, 1973a), animals (Price, 1971a; Thorn, 1978a; Smith and Gardner, 1985), needle-ice (Higashi and Corte, 1971: Mackay and Mathews, 1974a; Meentemeyer and Zippin, 1980), slope wash (Herz, 1964; Jahn, 1975; Lewkowicz, et. al., 1978; Stromquist, 1983) and snow creep (Williams, 1962a; Jahn and Cielinska, 1974; Thorn, 1978b).

Considering the breadth of the above influences it is perhaps not surprising to discover that solifluction takes many forms. Perhaps the most widespread expression of solifluction are solifluction sheets (French, 1976:139). Tending to mantle wide expanses of terrain, this form of solifluction produces relatively smooth blankets of low-angle sediment, particularly where the vegetation cover is limited or absent (c.f. Selby, 1971). In areas of greater relief or where vegetation hinders solifluction, more localized solifluction landforms are common. Prominent amongst this group of landforms are solifluction terraces, which exhibit a great range of sizes. Miniature terraces are characterized by small vertical risers only a few cms in height, separated by bare tread surfaces (c.f. Warren-Wilson, 1952; Benedict, 1970). Giant terraces are similar in form but cover much larger areas. Consisting of roughly horizontal upper tread surfaces, they are separated by frontal ramparts which are often several meters in height (c.f. Price, 1974:433; Luckman, 1981:106). Finally, where solifluction is concentrated into more well-defined linear pathways, lobate solifluction lobes are more common.

2.3 Solifluction Lobes

Solifluction lobes are emblematic of the solifluction process. In form and appearance they resemble large tongues of soil. Their longest dimension generally extends downslope 2.0 to 5.0 m (C.Harris, 1981a) at right angles to the local contour. They tend to have steep, often bulbous, frontal snouts which rarely exceed 1.0 m in height. Internally solifluction lobes usually consist of diamictons, dominated by sand- and silt-sized sediments (Benedict, 1976).

Lobes are commonly found on moderately steep slopes, from 10 to 20 degrees (Jahn, 1967; Schunke, 1974), but have been reported on slopes of much less (Dutkiewiez, 1967; Hall, 1981) and much greater (Mottershead and White, 1969; Graf, 1976) inclination. They tend to originate where random thickening (Young, 1972), topography (Embleton and King, 1975) or vegetation (Warren-Wilson, 1952) impounds faster moving sediments behind sluggish frontal banks (Rapp and Stromqust, 1979; Gamper, 1981). Consequently, solifluction lobes move downslope relatively slowly, with long-term rates of frontal movement averaging less than 0.5 cm/year (Table 2.1).

Table 2.1 : Long-term average rates of solifluction lobe movement determined by radiocarbon dating[1].

location	reference	oldest C^{14} date	mean rate of mov't (cm/yr)
Colorado	Benedict (1966,1970)	2470±110	0.32
Colorado	Benedict (1970)	2340±130	0.18
Australia	Costin et. al., (1967)	2980±180	0.16
Greenland	Everett (1967)	1695±140	0.12
Greenland	Everett (1967)	935±120	0.18
Scotland	White et. al., (1972)	5145±135	0.17
Norway	Worsley et. al., (1974)	2480±90	0.12
Norway	Worsley et. al., (1974)	2550±80	0.11
Switzerland	Furrer et. al., (1975)	1440±115	0.31
Alaska	Hamilton in Benedict (1976)	2075±130	0.11
Alaska	Hamilton in Benedict (1976)	2670±180	0.08
Norway	Ellis (1979)	4759±130	0.21
Yukon	Alexander et. al., (1980)	(28 dates)	0.07-1.0
Arctic	Dyke (1981)	2210±60	0.25
Switzerland	Gamper (1981,1983)	4580±85	0.17
Yukon	Rampton (1982)	1160±50	0.15
Alaska	Reanier et. al., (1983)	6610±100	0.32

1. derived in part from Dyke (1981:22).

2.3.1 Classification and Morphodynamics

Solifluction lobe formation is almost certainly polygenetic. Benedict (1970) recognized this and proposed a descriptive classification scheme, derived from parameters discussed by Lundquist (1949) and Washburn (1956), which identified two main types of solifluction lobes: stone-banked lobes and turf-banked lobes.

2.3.1.1 Stone-Banked Lobes

Stone-banked lobes are largely unvegetated and display marked sediment sorting. They are enclosed by steep embankments composed of stones and boulders without visible fines (c.f. Sharp, 1942; Benedict, 1970). The surfaces of these lobes are bare and exhibit signs of frost sorting. Characteristically, they develop on slopes between 10 to 20 degrees, yet they maintain essentially horizontal surfaces.

Stone-banked lobes represent a distinct form of solifluction favoured by enhanced frost action. They develop where coarse debris is moved more rapidly than fine debris (Benedict, 1976; Schwarz-Zanetti, 1983), and becomes concentrated along a stone-rich margin (Hall, 1981). Preferred locations are at the front of stone streams (Caine, 1963) or along the lower margins of scree slopes (Benedict, 1970) where solifluction is characterized by intense frost sorting (Price, 1970a) and minimal gelifluction (Jahn, 1975).

2.3.1.2 Turf-Banked Lobes

Turf-banked lobes are distinguished by, and probably strongly modified by, a covering mantle of vegetation and turf (Frodin, 1918; Carbiener, 1966; Raup, 1969). They are commonly found in tundra settings immediately downslope of lingering snowbanks (Jahn, 1967), or near the lower end of concave slopes (Rapp, 1960) where solifluction is channelized or locally intense (Rudberg, 1972; 1974). Typically, turf-banked lobes are stone-poor, being largely composed of frost-susceptible fine-grained debris (Williams, 1966; C.Harris, 1977).

Turf-banked lobes move in a variety of ways, with two basic formats recognized (Jahn, 1975:151-152). In the first type, accelerated motion in the uppermost soil layers is the primary transfer process. In extreme examples this results in rapid detachment failures which cascade over the snout, spreading sediment downslope (Siple, 1952; Price, 1969, 1974; Rampton and Dugal, 1974). More commonly, however, frontal bulging, precipitated by shallow shearing or sliding (Jahn, 1967; Price, 1970b), results when compressive flow forces shallower soil layers to progressively bury deeper horizons (Everett, 1967; Worsley and Harris, 1974; Furrer, et. al., 1975). Net downslope movement results when the growing frontal bulge ceases to expand and collapses downslope (Warren-Wilson, 1952; Williams, 1957). In other examples, the mantling vegetation cover actually appears to cause the uppermost soil layers to be gradually infolded by an overturning front (Rudberg, 1964; Dylik, 1969; Benedict, 1970; Ellis, 1979).

The second type of movement involves deep-seated basal sliding (Alexander and Price, 1980). In this form of motion, solifluction lobes appear to move downslope *en masse*, usually along internal discontinuities (Mackay, 1981; Reanier and Ugolini, 1983). However, this form of movement is largely restricted to active layer detachments above melting permafrost bodies.

2.3.1.3 Discussion

Precise classification of solifluction lobes is almost always problematic. Even though turf-banked lobes are characteristically somewhat smaller than stone-banked lobes (C.Harris, 1981a), the two share many morphological attributes (Embleton and King, 1975). Further, it is rarely possible to identify a dominant morphodynamic process because of long-term changes in the character of local solifluction (Furrer and Bachmann, 1972; Gamper, 1983). Finally, the visual criteria of sorting versus vegetation are often unreliable because a continuum of forms exists between these two lobe types (Harris, 1981a:282).

2.3.2 Alpine Solifluction Lobes

Solifluction lobes are widespread in the high alpine. Although similar in character to lobes found elsewhere, high mountain environments influence solifluction processes in two essential ways. First, high mountain settings increase the relative rate of solifluction and, second, high mountain climates affect their morphodynamic nature.

Solifluction movement rates in alpine areas are typically greater than those recorded in arctic regions (Young, 1974; Saunders and Young, 1983). While there are probably several reasons for this (C.Harris, 1981a:116), the most important stems from the physiographic character of high mountain landscapes. Most high mountain regions are characterized by a preponderence of relatively steep slopes and, consequently, tend to promote rapid sediment transfers (Hewitt, 1972; Caine, 1974). While this need not, of course, be true of alpine solifluction slopes, process measurements almost always confirm that it is (Benedict, 1970; C.Harris, 1972; Price, 1973).

Mountain climates affect solifluction in several ways. High mountains are characterized by well-marked and prolonged winter seasons (Flohn, 1974; Barry, 1981). The inherent climatic thresholds serve to define the **alpine periglacial zone** (Karte and Liedtke, 1981), which is usually considered to be the whole vertical range above the climatic treeline (Lundqvist, 1962). Within this zone Furrer (1965) and Troll (1972) have identified a number of climatic sub-belts, each of which is characterized by a distinctive suite of geomorphic processes. For instance, in the middle latitudes solifluction appears to be restricted to a relatively narrow altitudinal belt lying immediately above the local treeline (Graf, 1971; Furrer and Dorigo, 1972; Caine, 1978a, 1984). Evidently altitudinal changes in climate act to restrict the spatial distribution of solifluction. Karte and Liedtke (1981:127) for instance, suggest the lower altitudinal boundary of solifluction coincides with the -2.0° C mean annual isotherm, whereas the nival line controls the upper boundary.

Vertical changes in climate, as well as corollary vegetation (Billings, 1974), also affect the manner of solifluction. For example, turf-banked lobes are common only near the lower altitudinal boundary of solifluction where there is a nearly closed carpet of vegetation. Stone-banked lobes, on the other hand, predominate at higher elevations where the climate is more extreme and the vegetation cover less complete. In between these two zones, there tends to be a transition of lobe forms upwards from turf-banked to stone-banked varieties (Rudberg, 1972; C.Harris, 1976; 1982). This vertical zonation of forms develops because turf- and stone-banked lobes have distinct morphogenetic requirements. Turf-banked lobes develop at lower elevations where vegetation interferes with solifluction activity, while stone-banked lobes form at higher elevations where frost sorting presages solifluction motion.

Specific elements of mountain climates are themselves often responsible for the character of alpine solifluction, particularly in the middle latitudes (Hollermann, 1973; Troll, 1973b; Caine, 1978a). Midlatitude mountain climates are distinguished by pronounced diurnal and seasonal temperature fluctuations (Troll, 1958; Fahey, 1971). Both Young (1972:61) and C.Harris (1981a:7) have illustrated that the accompanying high freeze-thaw frequencies disproportionately encourage the frost creep component of solifluction. Midlatitude mountains are also characterized by high levels of precipitation, much of which occurs as winter snow (Barry, 1981). Prolonged melting of this accumulated snow during the spring promotes the localization of solifluction (Jahn, 1967; C.Harris, 1972). Finally, midlatitude mountains are strongly influenced by the prevailing westerlies (Barry, 1981) which affect the orientation of solifluction lobes by influencing the distribution of snowbanks and vegetation (Stocker, 1973, 1984; Hansen, 1976).

2.4 Chapter Summary

One can conclude from this review that the concept of solifluction is a convenient way of describing the geomorphic consequences of a whole suite of periglacial mass wasting processes. The relative importance of any one of them varies both spatially and temporally, although frost creep or gelifluction mechanisms seem to dominate. The geomorphic role of solifluction is, therefore, strongly conditioned by its local environmental and topographic setting.

In alpine locations the morphodynamic property of solifluction commonly results in the formation of turf-banked lobes, particularly at lower elevations where the mantling vegetation cover appears to modify the geomorphic expressions of the different solifluction processes. A large number of studies have examined solifluction processes in these settings, discovering distinctive morphoclimatic traits. However, relatively few studies have attempted to distinguish the specific geomorphic inputs of the different mechanisms. This is especially true of the North American cordillera where solifluction itself has attracted only limited attention.

3. THE FIELD AREA

3.1 Introduction

Solifluction landforms are a widespread morphological component of high alpine areas of the North American cordillera. Although they represent an important mass wasting process of this zone, detailed investigations of their nature and dynamics are largely limited to two benchmark studies. This work includes Benedict's (1966, 1970) examination of slow downslope movements in the Colorado Front Ranges and Price's (1969, 1970a, 1970b, 1971a, 1971b, 1973, 1974) study of solifluction lobe ecology in the Yukon Ruby Range. In the southern Canadian cordillera there has been almost no appreciation of the geomorphic significance of solifluction processes (c.f. Slaymaker and McPherson, 1977). While S. Harris (1971, 1973), Luckman (1973) and Slaymaker (1977) have confirmed the activity of slow mass wasting processes in this region, they did not specifically distinguish the role played by solifluction.

The aim of this research project was to establish the nature of solifluction mass wasting associated with turf-banked solifluction lobes located within the southern Canadian cordillera. It was completed within the Canadian Rocky Mountain region, where previously little was known about either the rate or character of solifluction activity (Gardner, 1979a; Luckman, 1981). This research program was designed to document these characteristics, and to assess the geomorphic significance of solifluction processes within this region.

The field area chosen for these investigations was the Alberta portion of the Canadian Rocky Mountains. It was selected, in part, because it afforded an excellent array of easily accessible, high alpine, solifluction landscapes. Although a number of workers had examined solifluction landforms within these settings (c.f. Karrasch, 1974; Bednarski, 1979), very little had been learned about the morphodynamics of the associated processes. Thus, there remained an opportunity to both document this activity and to establish its general character throughout this region.

3.2 Areal Setting

The Canadian Rocky Mountains form the eastern edge of the North American cordillera in western Canada. This rugged high mountain landscape stretches 1500 km southeastward from north-central British Columbia to the international border at the 49th parallel. Varying in width from 100 to 500 km, the Rockies are flanked to the west by the Rocky Mountain Trench and to the east by the Interior Plains.

The field area is located within the Alberta portion of the Canadian Rocky Mountains located between 50° and 53° N latitude (Figure 3.1). The field area extends eastwards from the continental divide straddling the Alberta-British Columbia border to the Inner Foothills. It encompasses part of Jasper National Park, Banff National Park, Kananaskis Provincial Park and parts of Kananaskis Country.

3.3 Physiography and Bedrock Geology

The average relief of the Alberta Rocky Mountain field area is over 2000 m asl, with the highest peaks reaching 2500 to 3500 m. This segment of the cordillera is characterized by a series of major ranges, all having northwest-southeast trends. These ranges are separated by deeply entrenched parallel valleys cut through by a number of eastward flowing rivers. Evidence of extensive valley and cirque glaciation is found throughout the area (McPherson, 1970; Rutter, 1972; Jackson, 1977), although at present only small ice caps and cirque glaciers are found scattered along/near the continental divide.

The Alberta Rocky Mountains consist of two high relief structural provinces. Along the interprovincial border, the massive castelled topography of the Main Ranges contains the regions highest peaks. Structurally part of the Eastern Main Ranges subprovince (Price and Mountjoy, 1970; Cook, 1975), these mountains are largely composed of relatively flat-lying to gently folded thrust blocks of lower Paleozoic carbonates and clastics (North and Henderson, 1954; Monger and Price, 1979). Immediately to the east, but separated from the Main Ranges by a series of major thrust faults, are the rugged Front Ranges. They consist of strongly folded

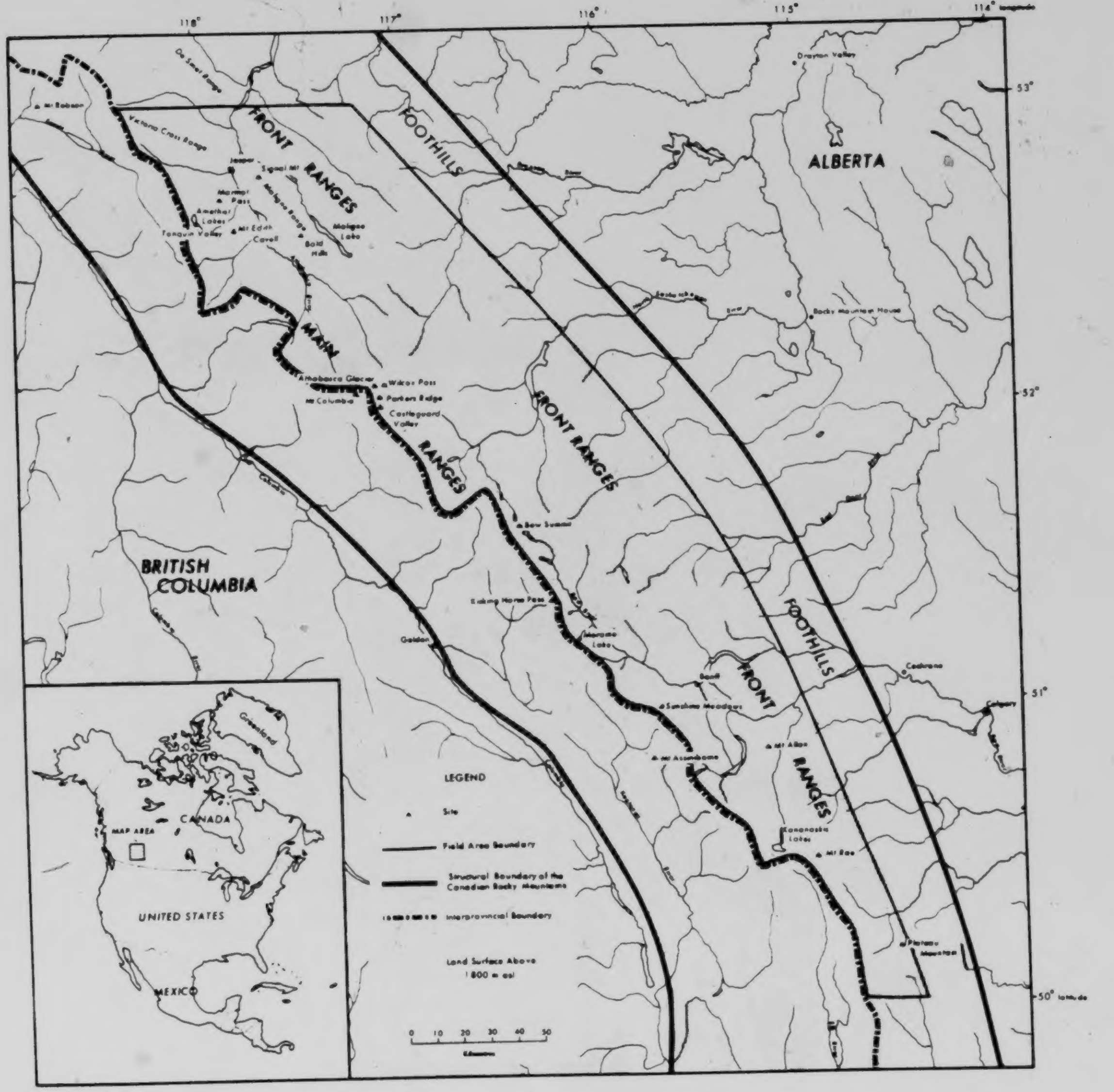

118°
117°
116°
115°
114° longitude
53°
52°
51°
50° latitude
FRONT RANGES
FOOTHILLS
MAIN RANGES
FRONT RANGES
FOOTHILLS
FRONT RANGES
ALBERTA
BRITISH COLUMBIA
Mt Robson
Victoria Cross Range
Jasper
Signal Mt
Marmot Pass
Amethyst Lakes
Tonquin Valley
Mt Edith Cavell
Maligne Range
Bald Hills
Maligne Lake
Athabasca Glacier
Wilcox Pass
Parkers Ridge
Columbia
Castleguard Valley
Bow Summit
Kicking Horse Pass
Golden
Moraine Lake
Banff
Sunshine Meadows
Mt Assiniboine
Mt Allan
Kananaskis Lakes
Mt Rae
Plateau Mountain
Drayton Valley
Rocky Mountain House
Cochrane
Calgary
Greenland
CANADA
MAP AREA
UNITED STATES
MEXICO
LEGEND
Site
Field Area Boundary
Structural Boundary of the Canadian Rocky Mountains
Interprovincial Boundary
Land Surface Above 1800 m asl
0 10 20 30 40 50
Kilometres

Figure 3.1 : The Alberta Rocky Mountain field area.

and thrust faulted Upper Cambrian to Jurassic-aged bedrock (Halladay and Mathewson, 1971). Near their eastern extremity, the Front Ranges are interlaced with younger rocks of Mesozoic age (Bielenstein et. al., 1971).

3.4 Climate, Vegetation and Soils

The climate of the Alberta Rockies is characterized as cold subhumid continental (Rheumer, 1953; Janz and Storr, 1977). Winters are long and cold, and often intensified by periodic incursions of Arctic air masses. In comparison, the summer period is both short and cool. Most of the precipitation received is derived from moist Pacific air. These macro-scale climatic patterns tend to be overshadowed locally where topography introduces a mosaic of topoclimates (Barry, 1981). The net result is a vertical climatic gradient and a multitude of microclimatic settings controlled by aspect and slope.

In response to these climatic gradations, the vegetation of the field area varies considerably (Ogilvie, 1969), although there tends to be a vertical gradation of vegetation with elevation upwards from montane to subalpine forests, to tundra life forms (Rowe, 1972; Ogilvie, 1976).

These parameters are reflected in the soils which characterize this region (Howell and Harris, 1978; Lavkulich and Sneddon, 1978). Among the most dominant are Brunisols, Gleysols and Regosols (Knapik and Coen, 1978; Holland and Coen, 1982). Permanently frozen ground is being encountered with increasing frequency at locations both above (Scotter, 1975; Harris and Brown, 1982) and below (Achuff and Coen, 1980) the present treeline.

3.5 Geomorphic Evolution

The deeply sculptured landscape of the Alberta Rockies is the result of recent geological upheavals and extensive Pleistocene glaciation. The eastern cordillera first formed before the mid-Cretaceous, although it was not until 20 million years ago that this orogenic phase was completed (Monger and Price, 1979). Since then denudation processes in Tertiary and

Pleistocene time have eroded this bedrock into the modern mountain forms (Ford, et. al., 1981).

The last major glaciation to affect the area occurred during the late Wisconsin when valley glaciers extended from the continental divide to positions near the eastern mountain front (Roed, 1968; McPherson, 1970; Rutter, 1972; Jackson, 1977, 1980). Recent work suggests deglaciation was under way by 13,000 year BP (Ferguson and Osborn, 1981; MacDonald, 1982) and was almost complete by 10,000 years BP, when the glaciers had receeded to positions close to or inside their present limits (Henoch, et. al., 1979; Luckman and Osborn, 1979; Kearney, 1981).

The legacy of these events is a high mountain setting profoundly accentuated by glaciation (Trenhaile, 1976, 1979). Geomorphic changes in postglacial time, have been of a much more subdued character (Gardner, 1979a). Glacial advances during the Holocene were limited in extent and duration (Luckman and Osborn, 1979; Osborn, 1982), and had little impact on the alpine landscape (c.f. Hallet and Anderson, 1980). Other geomorphic agents, such as fluvial, mass wasting and periglacial processes, have similarly been responsible for only relatively minor changes to this mountain setting in the last 10,000 years (Luckman, 1981). Nevertheless, there is ample evidence of their influence on the geomorphology of this alpine landscape (c.f. Slaymaker and McPherson, 1977).

3.6 Previous Observations of Solifluction Activity in the Alberta Rocky Mountains

Morphological evidence of solifluction activity is widespread in the Alberta Rocky Mountains. Turf-banked solifluction lobes for instance, are a common landform feature of alpine settings in this area (c.f. Holland and Coen, 1982, 1983). In the Victoria Cross Ranges of Jasper National Park, Hamilton (1981) observed turf-banked solifluction lobes encroaching upon treeline. Slightly further to the east, in the De Smet Range, Hettinger (1975) observed solifluction lobes located at 2135 m on Gargoyle Mountain. In the Maligne Range to the south, Hrapko (1970:134-156) concluded that there was considerable evidence of contemporary solifluction movement on Signal Mountain. In the same general area, Luckman (1973) described solifluction movements in Surprise Valley, while Kuchar (1975:25) commented on solifluction landforms located in the Bald Hills west of Maligne Lake. West of the Athabasca River in the Park Ranges, Bednarski (1979:100) described what he considered to be active solifluction lobes in Marmot Pass. Nearby, in the alpine meadows which surround Mt. Edith Cavell, Luckman (1981:106) found giant solifluction lobes which may be active at the present time. Solifluction lobes are also common in nearby Tonquin Valley, where Kershaw (1977) estimated the lower altitudinal boundary of solifluction to be around 2180 m asl in the vicinity of the Amethyst Lakes. At the southern end of Jasper National Park, solifluction lobes were described by Karrasch (1974:292) in Wilcox Pass above the Athabasca Glacier.

By contrast, observations of solifluction activity in Banff National Park are fewer and less detailed. Karrasch (1974), for example, described turf-banked lobes found at Parkers Ridge but noted only that lingering snowpacks appeared to be indirectly assisting gravitational movements. Ford (1971:243; 1983:433) and Luckman (1981:94) noted that solifluction lobes were actively advancing in the nearby Castleguard Valley. Apparently climatic deterioration in the most recent Neoglacial period has mobilized the local clay-rich till as solifluction lobes (Ford, 1979). Further to the south, Gardner (1968, 1978) mapped the areal distribution of solifluction landforms in the Moraine Lake area, while Knapik, et. al., (1973) noted the activity of solifluction processes in the Sunshine Meadows.

There are few reports of solifluction activity outside the two National Parks. In the northern reaches of the field area Mortimer (1978) examined solifluction landforms in the vicinity of Prospect Mountain. Much further to the south in the Kananaskis Valley, S. Harris (1971, 1973) measured relatively rapid rates of soil creep above treeline which likely include elements of solifluction (Slaymaker and McPherson, 1977:175; Luckman, 1981:106). Additional observations of solifluction in the Kananaskis region have been of a reconnaissance nature, although they do confirm its widespread, if localized, occurrence (Milus Tress and Baron, Ltd., 1976). For example, solifluction processes appear to be active in the Marmot

Creek Experimental Basin (Beke, 1969; Richards, 1981) and in the vicinity of Highwood Summit (Trottier, 1972; Tarquin, 1977; D.Smith, 1979). Slightly further to the south, solifluction activity on Plateau Mountain appears to be quite restricted (Bryant and Scheinberg, 1970; Woods, 1977).

Despite these widespread observations of solifluction, it remains difficult to gauge the behavior of solifluction processes in this region. Mapping the locations of these observations along a latitudinal transect of the Alberta Rockies did reveal that solifluction is apparently restricted to a 200 m altitudinal belt located at/above the present-day treeline (Figure 3.2).

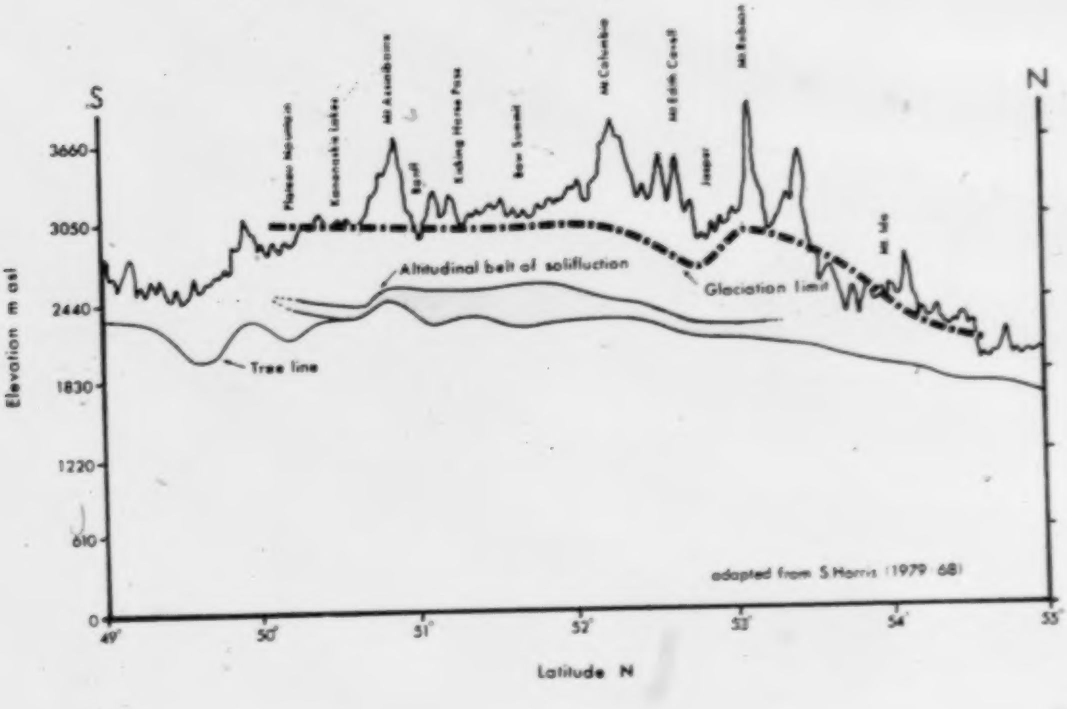


Figure 3.2 : Altitudinal belt of solifluction lobes mapped within the Alberta Rocky Mountain field area. Height of the highest mountain east of the continental divide after S.Harris (1979:68).

The lower altitudinal boundary of this belt decreases in elevation northwards, from around 2400 m asl at 50° latitude to 2000 m asl at 53° latitude. The southern extent of this solifluction zone is unknown, although increased aridity and a general lowering of the landscape south of 50° latitude must restrict its occurrence.

Turf-banked solifluction lobes appear to be well represented within this altitudinal solifluction zone, exhibiting signs of both historical (Ford, 1983; Gardner, et. al., 1983) and contemporary (Hrapko, 1970; Bednarski, 1979) activity. The data reviewed also suggest that climate (Ford, 1971, 1979), moisture (Hrapko, 1970; Karrasch, 1974) and sediment (D.Smith, 1979; Ford, 1983) are among the many parameters controlling solifluction in this region.

3.7 Conclusions

These observations illustrate that solifluction is an important geomorphic agent in the Alberta Rocky Mountain region. Despite this not a single investigation had been undertaken to substantiate its geomorphic character. As a consequence this study was initiated in 1980 to complete a regional appraisal of solifluction mass wasting within the Alberta Rockies.

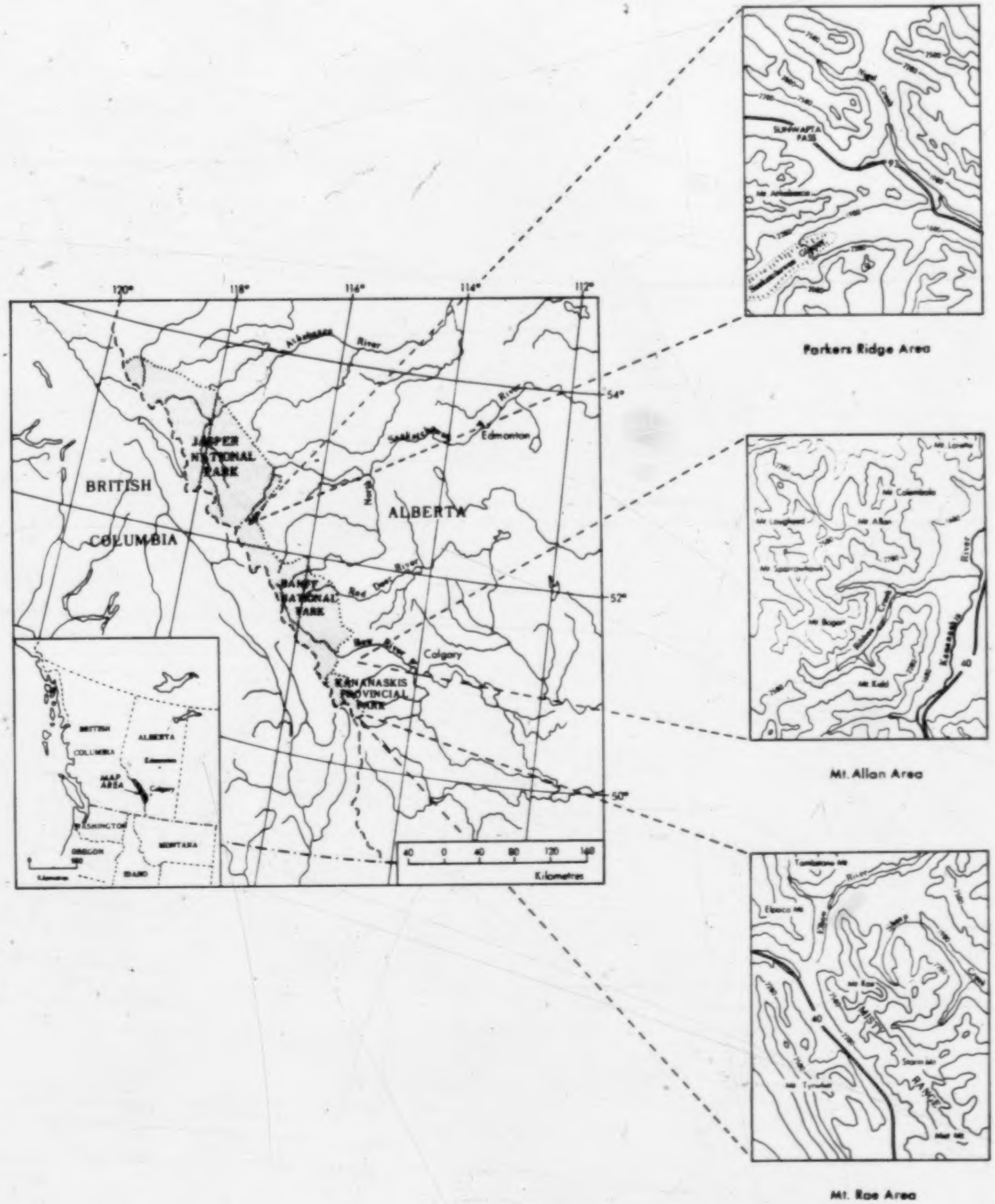
4. THE RESEARCH SITES

4.1 Introduction

In order to accomplish the objectives of this research program, three study areas located within the Alberta Rocky Mountains were identified: the Mt.Rae area located in the southeast corner of Kananaskis Provincial Park; the Mt.Allan area in Kananaskis Country; and the Parkers Ridge area in northern Banff National Park (Figure 4.1). These areas are characteristic of the broad range of landscape assemblages found within this region. For example, the Parkers Ridge area contains solifluction sites typical of those within most Main Range settings. On the other hand, the Mt.Rae and Mt.Allan areas contain solifluction landscapes characteristic of Front Range environments. By conducting parallel investigations within each of these areas, it was anticipated that a more comprehensive appraisal of the typical rate of solifluction would be generated.

For comparative purposes, a number of distinct study sites were identified within each of the three study areas. Selected during the preliminary reconnaissance of each area, these sites were situated wherever there was a significant morphological expression of turf-banked solifluction lobe activity. This site selection criteron was utilized after a review of the previously published literature and a general appraisal of the field area confirmed that turf-banked lobes represented the most common morphological expression of solifluction within this region and, thus, were probably representative of its general character.

At each of the study sites select numbers of lobes were identified for long-term monitoring and/or investigation. While these were chosen as representative examples of the morphological character of turf-banked lobes at a particular site; the most important consideration in their selection was that they corresponded to the criteria set forth by Benedict (1970). Hence, most of the study lobes were tongue-shaped and had lobate, well-vegetated, frontal perimeters. Figures 4.2 and 4.3 illustrate two typical examples of the turf-banked lobes selected for study.


Parkers Ridge Area

Mt. Allan Area

Mt. Rae Area
120°
118°
116°
114°
112°
54°
52°
50°
Athabasca River
JASPER NATIONAL PARK
BRITISH COLUMBIA
ALBERTA
Edmonton
North Saskatchewan River
Red Deer River
BANFF NATIONAL PARK
Bow River
Calgary
KANANASKIS PROVINCIAL PARK
BRITISH COLUMBIA
ALBERTA
MAP AREA
WASHINGTON
OREGON
IDAHO
MONTANA
40
0
40
80
120
160
Kilometres
SUNWAPTA PASS
Mt. Athabasca
93
Mt. Lorette
Mt. Collembola
Mt. Lougheed
Mt. Allan
Mt. Sparrowhawk
Mt. Bogart
Mt. Kidd
Kananaskis River
Elbow River
Mt. Rae
MISTY RANGE
Storm Mt.
Mt. Tyrwhitt
40
Sheep Creek

Figure 4.1 : Location map of the three study areas.

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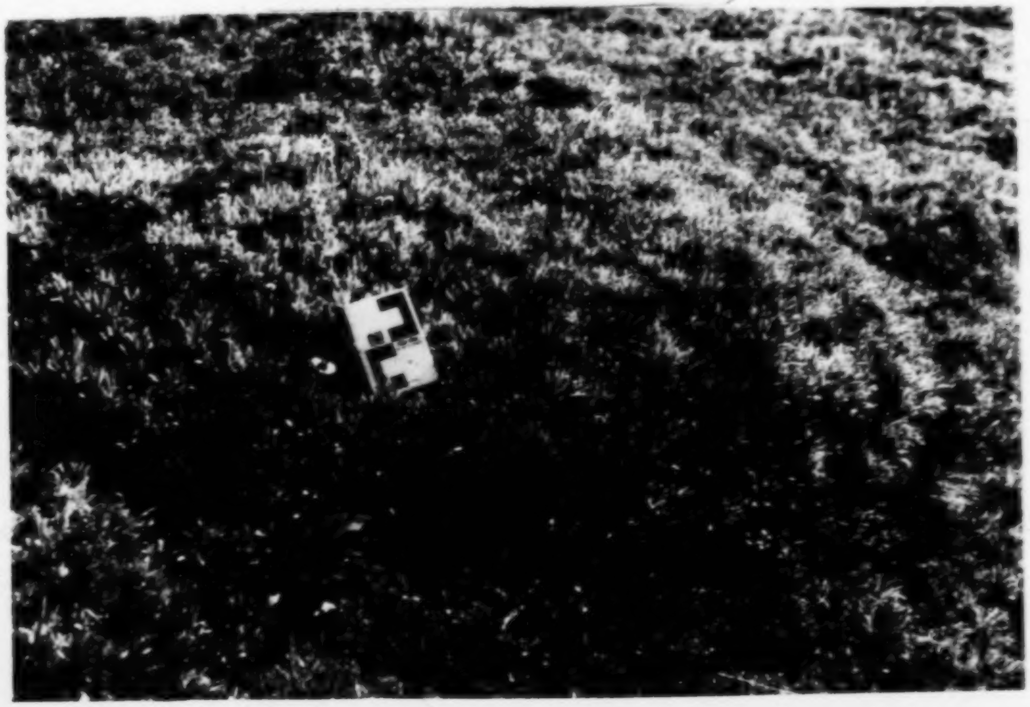

Figure 4.2 : A small turf-banked solifluction lobe (Lobe 34) located in the Mt.Rae study area. Note the field-notebook for scale.

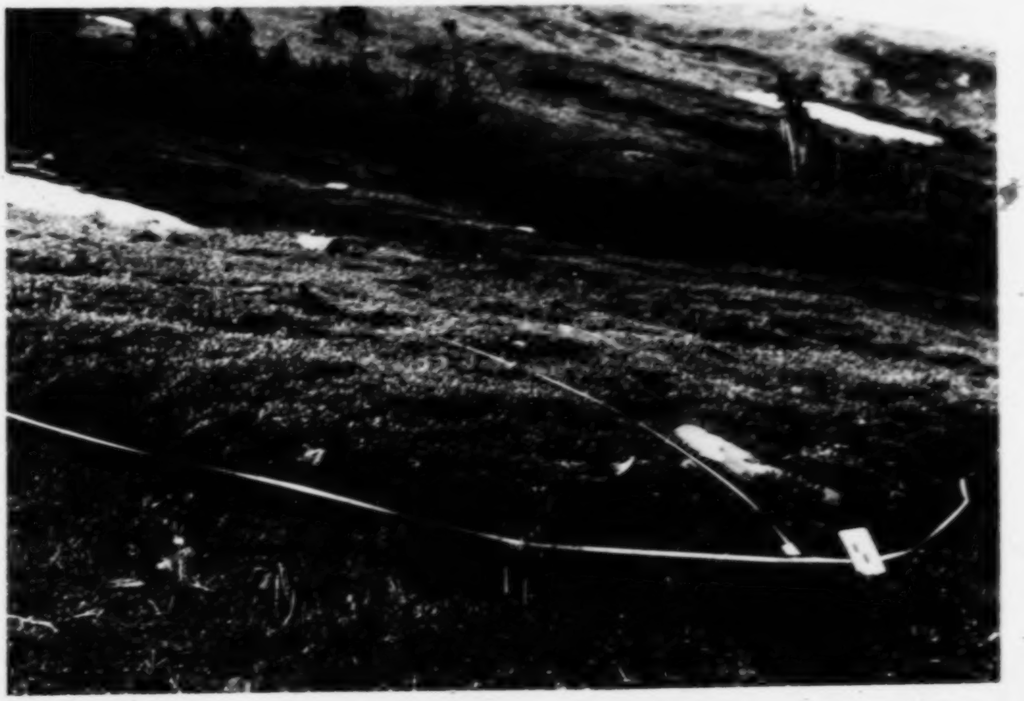

Figure 4.3 : A large turf-banked solifluction lobe (Lobe 49) located in the Parkers Ridge study area. Note the field notebook for scale.

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In total, 58 turf-banked solifluction lobes were identified for study within the general field area. Each one of these individual study lobes was assigned a numerical identifier, from #1 to #62, which served to distinguish it throughout the research program [1]. Twenty-seven of these lobes were located in the Mt.Rae area, sixteen in the Mt.Allan area and fifteen in the Parkers Ridge area. The location of each study lobe and the characteristics of each of the study sites are presented within the following discussions of the three study areas.

4.2 The Mt.Rae Area

The Mt.Rae area is a 100 km² segment of high alpine country located within the Front Ranges of the Alberta Rocky Mountains at 50° 35' N latitude and 116° 06' W longitude (Figure 4.1). Situated about 75 km southwest of Calgary, this area contains headwater tributaries of the Elbow, Highwood, Kananaskis and Sheep Rivers (Figure 4.4).

The steep mountainous topography of this area is a consequence of local geologic structures (Figure 4.5). Folding and thrusting of sedimentary strata have interlaced rocks of Mesozoic age amongst the rugged Elk, Misty and Opal Ranges composed of resistant Paleozoics (Halladay and Matthewson, 1971; Ollernshaw, 1975). These NNW-SSE oriented mountain ranges, composed predominantly of limestone/dolomite (MacQueen and Bamber, 1968), stand in sharp contrast to the parallel but lower elevation Mesozoic ridges composed of sandstone, shale and coal (Allan and Carr, 1947; and Figure 4.5).

Extensive glaciation has deeply sculptured the Mt.Rae landscape (Jackson, 1977, 1980; Gardner, et. al., 1983). The major valleys are U-shaped (Allan and Carr, 1947; Hawes, 1977) recording maximum ice depths of between 140 to 215 m. Nunataks which stood above the glacial limit (Harris and Waters, 1977) illustrate extreme periglacial weathering. Nearby evidence suggests the most recent phase of valley glaciation was in full retreat by 13,500 years BP (Harrison, 1976; Ferguson and Osborn, 1981, 1982). Since then, glacial activity in this area

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[1] Initially, 62 lobes were selected for study. However, four lobes were eventually discarded when it became apparent that their relative remoteness was going to make repeated visits problematic.

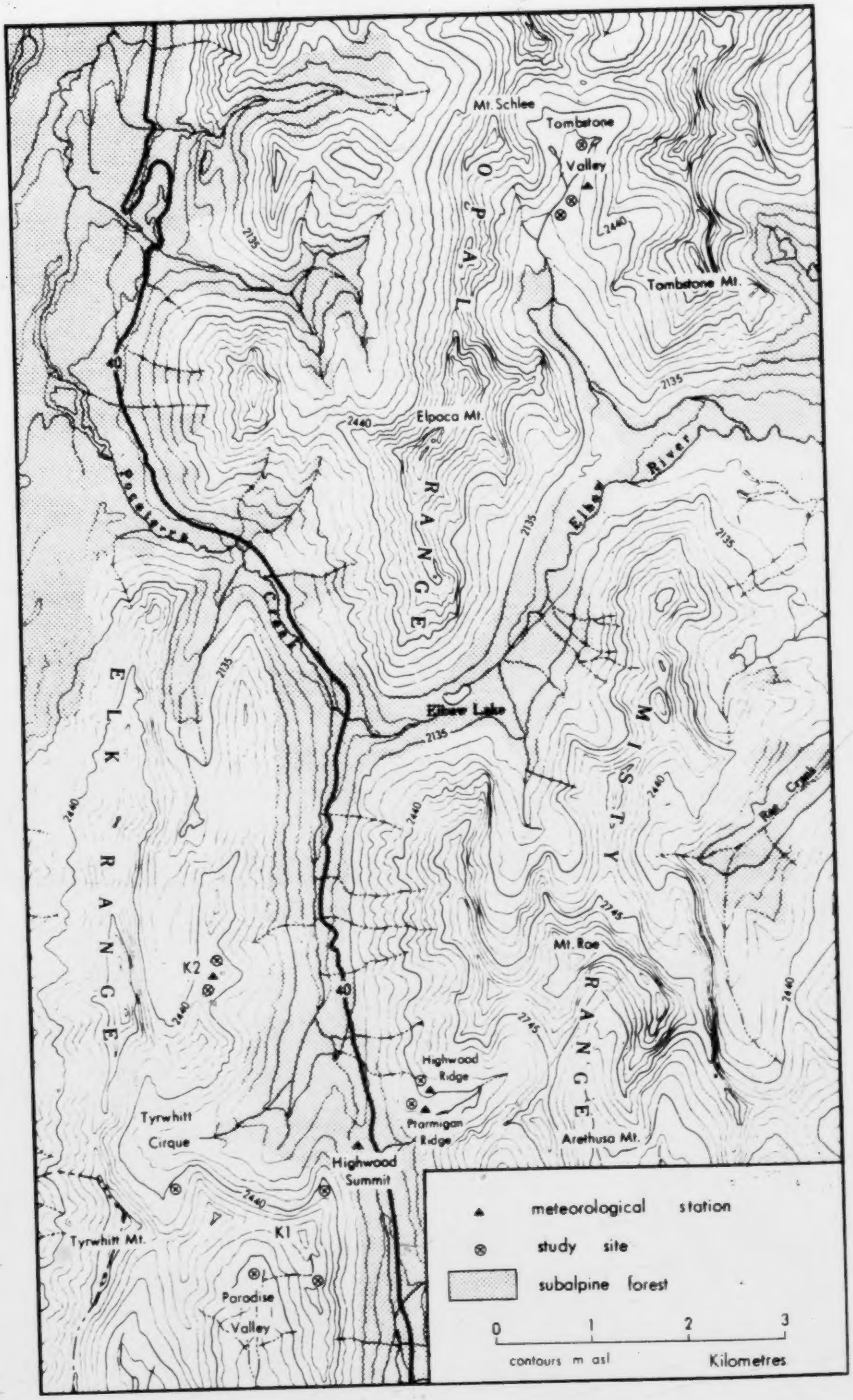
Mt. Schlee
Tombstone
Valley
OPAL RANGE
Tombstone Mt.
Elpoca Mt.
Elbow River
Pocaterra Creek
ELK RANGE
MISTY RANGE
Elbow Lake
Rae Creek
Mt. Rae
K2
40
Highwood Ridge
Ptarmigan Ridge
Tyrwhitt Cirque
Highwood Summit
Arethusa Mt.
Tyrwhitt Mt.
K1
Paradise Valley
2135
2440
2745
▲ meteorological station
⊗ study site
▨ subalpine forest
0
1
2
3
contours m asl
Kilometres

Figure 4.4 : The Mt.Rae study area.

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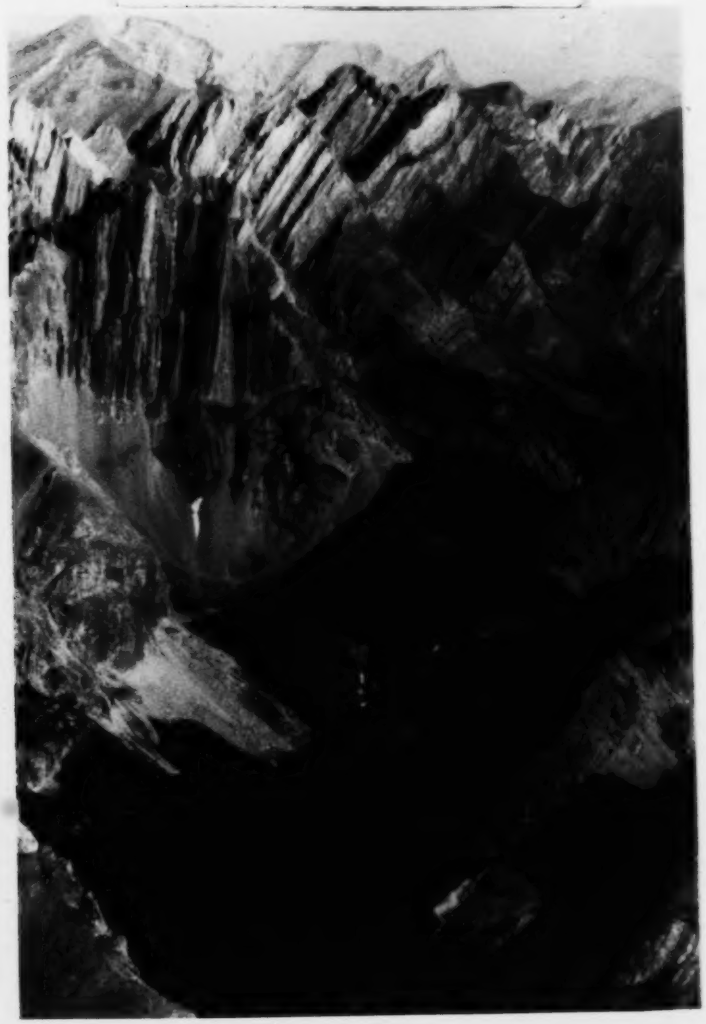

Figure 4.5 : The view north from the summit of Mt.Rae overlooking Tombstone Valley. Note the steeply dipping Paleozoic strata which overshadow the subdued Mesozoics which line the valley floor.

has been restricted to cirque locations, where limited advances during the early Holocene and Neoglacial are recorded (Jackson, 1977; D.Smith, 1979). In much the same way the activities of other geomorphic systems within this area have operated with decreased intensity over Holocene time (Gardner, et. al., 1983:207-208), resulting in a broad selection of alpine landforms (Tarquin, 1977; Smith and Gardner, 1979; Gardner, 1983a, 1983b).

Pedological activity within the alpine of the Mt.Rae area has resulted in an array of Brunisols and Regosols (Trottier, 1972), with Regosols more dominant in the upper alpine zone where the sediments are relatively unstable (Baig, 1972). Exposed ridges and flats within the local alpine zone are characterized by communities of *Salix reticulata*, *Dryas octopetala* and *Kobresia myosuroides*. More protected sites are defined by associations of *Phyllodoce aleutica*, *Cassiope tetragona* and *Carex nigricans* (Trottier, 1972).

Paleoclimates in the Mt.Rae area have fluctuated throughout the Holocene. Following deglaciation relatively cool climates persisted until about 9700 years BP (Ferguson, 1978). This period was succeeded by warmer temperatures from 9700 to 8700 years BP, and a short-lived cool period from 8700 to 8300 years BP (Driver, 1978; Ferguson, 1978; MacDonald, et. al., 1980). From 8300 to about 5700 years BP local temperatures were much warmer and drier than they are at the present (Ferguson, 1978). Following this hiatus the local climate gradually deteriorated (Christensen and Hills, 1971; Bujak, 1974), until between 3500 to approximately 1700 years BP when slightly cooler temperatures persisted (Ferguson, 1978; Wilson, 1979). This period was followed by a minor warming trend, until the last millenia when climatic deterioration culminated in the Little Ice Age (Luckman and Osborn, 1979).

The present climate of the study area is distinctly continental. The mean annual temperature at Highwood Summit (2175 m asl) is -1.8° C (Table 4.1), ranging from a summer average of 6.1° C (May to September) to a mean temperature of -11.0° C in the coldest winter month (December). The extreme minimum temperature recorded at Highwood Summit was -44.4° C (December 29, 1968), while the extreme maximum was 27.1° C (August 1, 1971). The number of days with frost averages 263 annually, with frost alteration days peaking in May (20

Table 4.1 : Mean monthly temperature (°C), Highwood Summit, Mt. Rae area[1].

Month	Maximum	Average	Minimum
January	6.0	-9.8	-35.6
February	8.3	-10.0	-28.6
March	7.2	-7.8	-30.6
April	12.2	-5.1	-23.3
May	18.3	2.0	-16.7
June	23.8	6.1	-6.1
July	23.9	9.0	-2.2
August	27.2	10.5	-2.8
September	23.9	3.0	-13.3
October	18.3	-1.4	-22.8
November	6.7	-7.1	-26.7
December	6.5	-11.0	-44.4
annual mean		-1.8	

1. unpublished, 1966-1973, (Atmospheric Environment Services), unpublished, 1981-1983 (Alberta Recreation and Parks).

Table 4.2 : Mean monthly precipitation (cm), Highwood Summit, Mt. Rae area[1].

Month	Maximum	Average	Minimum
January	15.2	5.0	0.5
February	17.8	6.3	2.0
March	12.7	7.1	3.3
April	14.0	8.4	2.8
May	15.2	9.8	5.1
June	17.8	10.0	4.1
July	9.7	6.4	2.8
August	13.5	7.2	1.3
September	11.2	6.3	3.8
October	9.4	5.3	2.5
November	15.2	6.7	1.8
December	13.0	8.2	2.8
annual total		86.7	

1. Environment Canada, 1969-1981, Supplementary Precipitation Data, Atmospheric Environment Services, Downsview.

days) and October (18 days).

Precipitation at Highwood Summit annually averages 86.7 cm (Table 4.2). A large proportion of this (33 percent) occurs between April and June, when heavy falls of snow are common in the area (c.f. Janz, 1976). Approximately 60 percent of the total precipitation occurs as winter snow (Baig, 1972). Particularly at higher elevations, strong winter winds (Trottier, 1972), redistribute much of this snow to build large snowbanks which commonly persist until mid-July.

4.2.1 Study Sites

During annual visits to the Mt.Rae area between 1977 to 1979, solifluction lobes were discovered in a wide variety of settings (Smith, 1979). In 1980, 27 turf-banked lobes located at 7 study sites were selected for detailed study over the next three years. The general terrain and biophysical features of these study sites are summarized in Table 4.3. Detailed descriptions of the various sites are provided in sections 4.2.1.1. to 4.2.1.7.

4.2.1.1 Highwood Ridge

The Highwood Ridge site occurs on the apex of a conspicuous valley-side bench located to the east of Highwood Summit (Figures 4.4 and 4.6). Topographically, the site is a relatively flat, northwesterly dipping surface which drops precipitously to the north, west and south but rises to meet a relatively steep bedrock freeface on its eastern perimeter.

Located at 2430 m asl, the Highwood Ridge site sits above the local glacial limit established during the last major valley glacier episode (Hawes, 1977). It is underlain by deeply-weathered Triassic shales (> 2.0 m) which have formed a clayey sediment relatively free of coarse fragments. Mudboils and solifluction landforms decorate this surface (D.Smith, 1979:94-99) and appear to be influenced by the presence of a sporadic permafrost body shown to exist at depths greater than 2.0 m along the bench axis (Gardner, et. al., 1983:42-44).

Highwood Ridge is mantled by alpine tundra. Because of the generally moist subsurface conditions and limited winter snowfall accumulations, this vegetation cover is characterized by

Table 4.3 : General geomorphic features of the Mt.Rae area study sites.

study site	altitude (m asl)	aspect	landform	bedrock lithology	genetic material	soils	vegetation (dominant)	study lobes
Highwood Ridge	2430	NW	valley bench	Triassic shales	colluvial	Regosols	dwarf shrub (*Salix* ssp.)	15
K1	2455 2485	NW-NE	nivation hollow	Kootenay sandstone	colluvial	Regosols Brunisols	dwarf shrub (*Salix* ssp.	3, 48
K2	2525	SW-W	nivation hollow	Kootenay sandstone	colluvial	Regosols	dwarf shrub (*Salix* ssp.)	10, 11, 12, 13, 14, 21 41, 43
Paradise Valley	2400	E	valley floor	Kootenay sandstone	colluvial	Regosols	herb -shrub (*Antennaria* ssp.)	4, 27 28, 29
Ptarmigan Ridge	2390	SW	valley bench	Triassic shales	colluvial	Regosols	herb -shrub *Antennaria* ssp.)	34, 35, 42 44, 45
Tombstone Valley	2310 2476	SW-NE	valley floor	Paleozoic limestone	colluvial /glacial	Regosols Brunisols	dwarf shrub (*Salix* ssp.)	1, 2, 23 24, 25, 26
Tyrwhitt Cirque	2412	NW	valley side	Kootenay sandstone	colluvial	Regosols	herb -shrub (*Dryas* ssp.)	22

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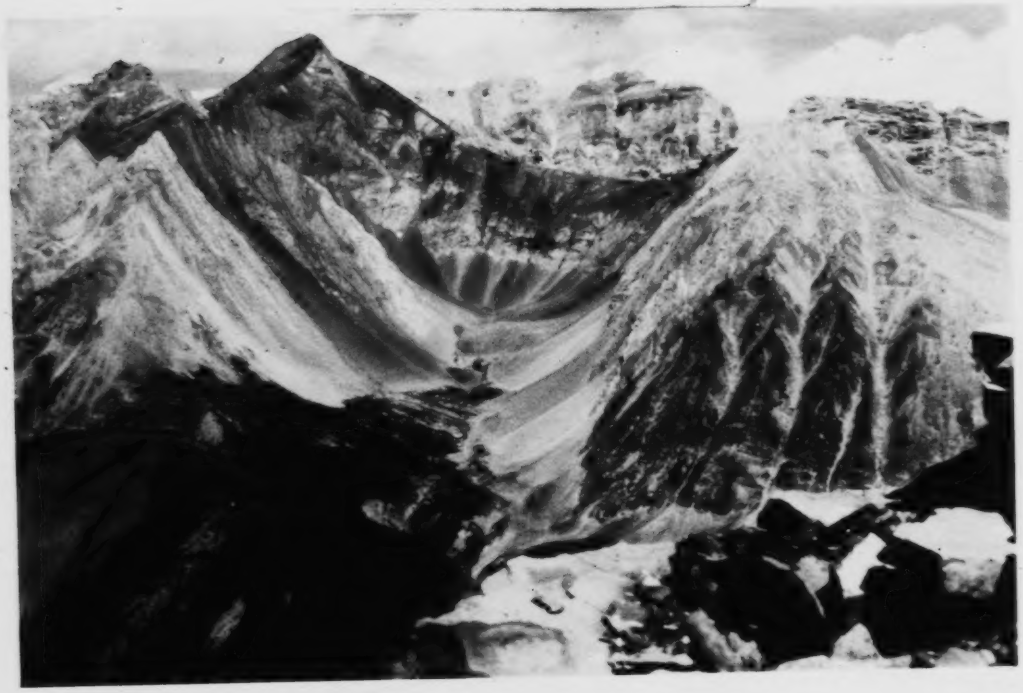

Figure 4.6 : The view east towards Mt.Rae and Arethusa Cirque. The Highwood Ridge site is indicated by the uppermost arrow, while the location of the Ptarmigan Ridge site is shown by the lower arrow.

Salix arctica and *Salix reticulata* communities.

A single lobate solifluction lobe, Lobe 15, was identified for continuing study in 1980 at this site. Located near the northern lip of the bench surface, Lobe 15 is situated downslope of a moss-covered seepage site. It has a bulging, completely vegetated snout which overlooks a prominent break-in-slope.

4.2.1.2 K1

K1 is a high-elevation bedrock ridge composed of Kootenay strata lying immediately to the southwest of Highwood Summit (Figure 4.4). Poorly-vegetated above treeline, the ridge contains a number of conspicuous nivation hollows along its linear apex. These hollows are characterized by well-weathered sandstone and coal felsenmeer deposits and downslope colluvial aprons blanketed by overlapping solifluction lobes. Two different lobe sites, at Lobe 3 and Lobe 48, were identified for long-term monitoring (Table 4.3). Both sites are located well above the local late-Wisconsin glacial limits (Hawes, 1977; Jackson, 1977).

Lobe 3 is situated within a well-weathered and in places gullied pocket of moderately sloping (20°) colluvium near the northern end of K1 at 2455 m asl (Figure 4.7). Facing to the northwest and mantled by a lingering snowpack until late-June, Lobe 3 is only sparsely vegetated by *Phyllodoce aleutica* and/or *Salix reticulata* plant communities. Pedogenic development at the site is limited to Regosols, except where localized volcanic ash deposits (Mazama?) have prompted the development of Brunisolic horizons. The lobe is located at the colluvial slope base, where the lower angle nivation hollow floor apparently encouraged its formation.

The site of Lobe 48 lies to the south of Lobe 3 along the ridge apex at 2485 m asl (Figure 4.4). It is situated in a relatively flat area of seasonal saturation below a large late-lying snowpack. Essentially unvegetated except for its frontal snout, this relatively small lobe typifies those found along this ridge crest.

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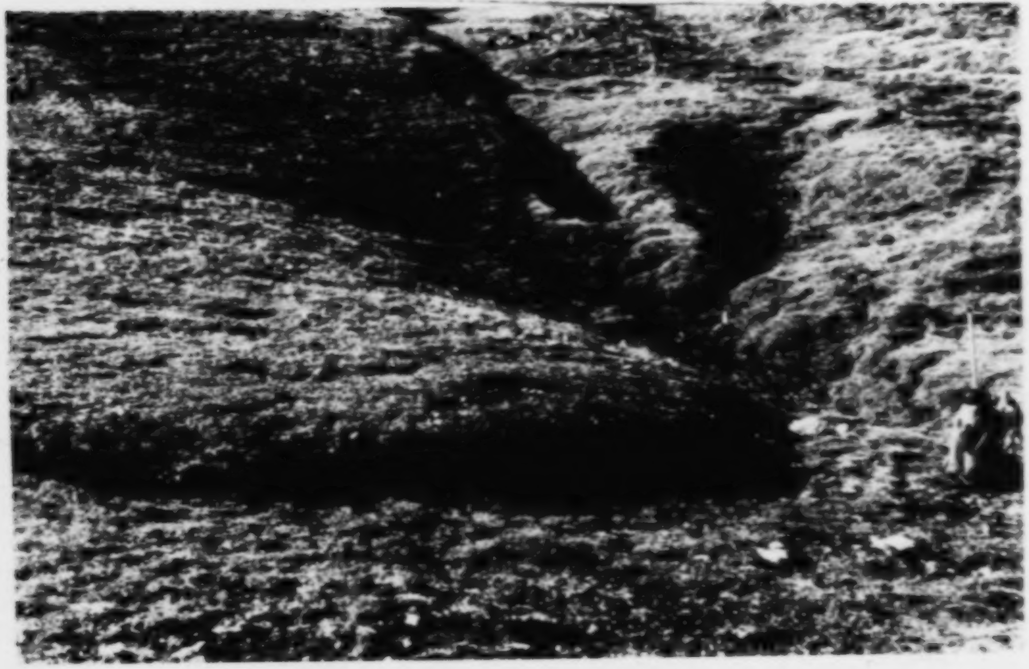

Figure 4.7 : The setting of Lobe 3 located on the northern limb of the K1 study site. The pack located in the right corner of the photograph provides scale.

4.2.1.3 K2

The K2 study site sits in a large, generally west-facing, nivation hollow on the summit of a ridge of Kootenay-age strata (Figure 4.8) located to the northwest of Highwood Summit (Figure 4.4). Situated well above the local glacial limit, at 2515 m asl, the K2 site has a moderate surface slope which ranges locally from 15 to 20°.

The K2 site is veneered by a well-weathered colluvial mantle derived from the local sandstones, coals and shales (Table 4.3). This cover contains only a few coarse cobbles and stones, and is generally well-drained. Pit excavations in late August of 1978, and again in 1982, revealed that frozen soils persist at relatively shallow depths (>1.5 m) late into the summer season, suggesting the possibility of sporadic permafrost.

The K2 site is typified by a vegetational cover dominated by *Salix arctica* and Regosolic soils. This biophysical pattern appears to be a consequence of the large winter snowpacks which usually persist until late July. Because of an abundance of moisture during the snowmelt period saturated conditions are common at the site.

The K2 site contains a relatively large number of turf-banked solifluction lobes. In total, eight lobes (Lobes 10, 11, 12, 13, 14, 21, 41, 43) were identified for long-term monitoring. The majority of these lobes are situated mid-way up the southern limb of this nivational hollow (Figure 4.9) . Facing predominantly to the west, these lobes are characteristically well-vegetated and have conspicuously bulging snouts. Winter snow accumulations in the vicinity of these lobes generally exceeds 2 m in depth.

A single lobe, Lobe 12, was located on the much drier northern limb of this nivational hollow. Facing to the southwest, this lobe is poorly vegetated except around its banked snout where *Salix arctica* dominates. Primarily because of its local exposure, winter snow accumulations at this location only rarely were observed to be greater than 1 m in depth.

4.2.1.4 Paradise Valley

The Paradise Valley study site is located within the alpine headwaters of a narrow south-facing tributary valley of the Highwood River west of Highwood Summit (Figure 4.4).

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Figure 4.8 : The K2 study site. The arrow points to the location of the lobes under investigation. In the immediate background is the northern limb of the K1 study site.

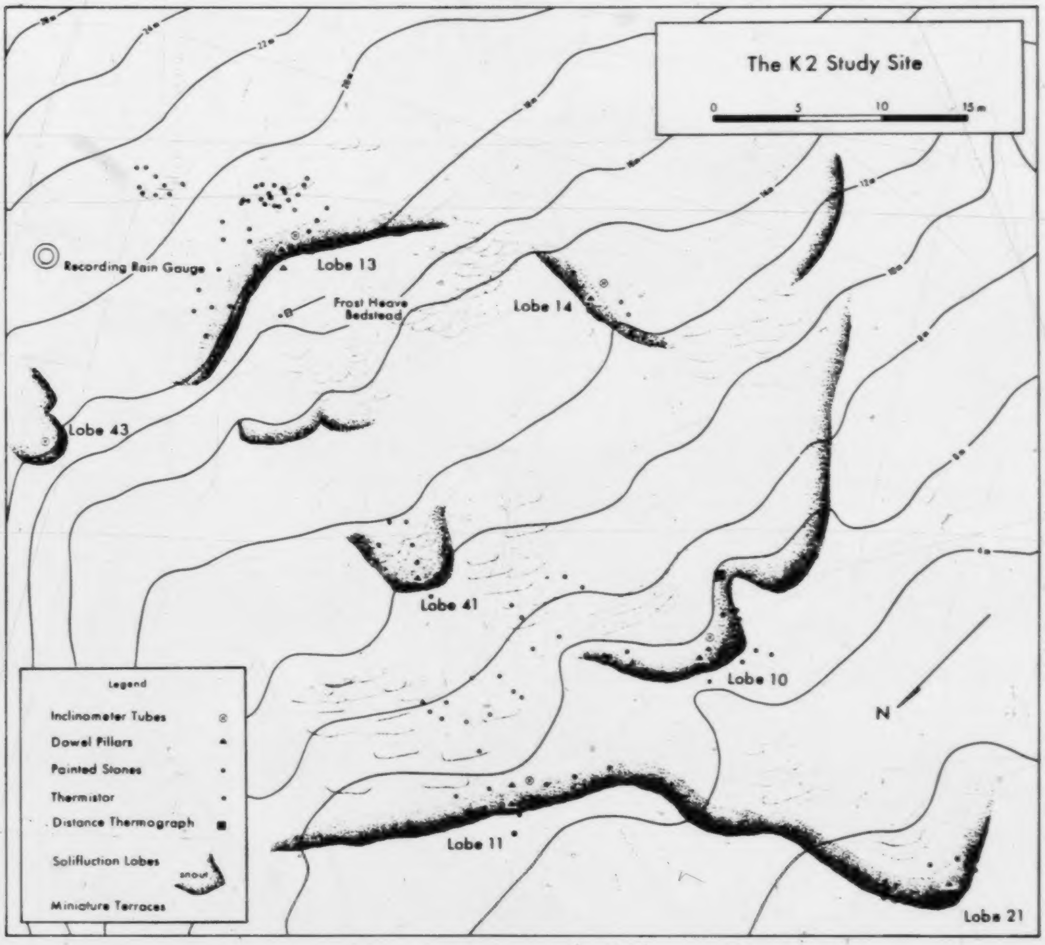
The K2 Study Site
0
5
10
15 m
Recording Rain Gauge
Lobe 13
Frost Heave Bedstead
Lobe 14
Lobe 43
Lobe 41
Lobe 10
N
Lobe 11
Lobe 21
Legend
Inclinometer Tubes
Dowel Pillars
Painted Stones
Thermistor
Distance Thermograph
Solifluction Lobes
snout
Miniature Terraces

Figure 4.9 : The K2 study site. Illustrated are the spatial relationships of the study lobes and the instrumentation sites.

The valley bottom is filled with colluvial debris weathered from the surrounding Kootenay-age mountain walls (Table 4.3). It is lushly vegetated by an extensive alpine tundra in its upper headwaters (Figure 4.10). There is no evidence of recent glacial activity within the valley.

Four east-facing turf-banked lobes (Lobes 4, 27, 28, 29) were selected for study at this site. Located near the valley head at 2390 m asl, these lobes are situated below a prominent seepage and lingering snowpack site. These lobes have relatively steep, well-vegetated frontal banks and are composed primarily of fine grained colluvial debris with few coarse fragments. Pedogenic activity at the four sites is limited to a relatively thick turf mat. Prominent in the vegetation are ***Potentilla diversifolia*****,** ***Antennaria lanata*** and ***Juncus drummondii*** species.

4.2.1.5 Ptarmigan Ridge

The Ptarmigan Ridge site is located below the southwest flank of Highwood Ridge to the east of Highwood Summit (Figure 4.4). Situated immediately above the local treeline at 2390 m asl, this site dips moderately (21°) to a small valley-side bench (Figure 4.6). Turf-banked lobes mantle the local footslope, particularly below the site of a late-lying snowbank which generally persists until late June.

While Ptarmigan Ridge is located just below the local glacial limit, postglacial weathering has spread a colluvial mantle across the site. Five lobes (Lobes 34, 35, 42, 44, 45) were identified for study. These medium sized, spoon-shaped lobes, are characteristically well-vegetated by a herb-dwarf shrub community dominated by ***Antennaria lanata*** and ***Vaccinium scoparium***. They are composed primarily of fine-grained sediments containing a small percentage of clasts. Soil development at these lobe sites is limited, with only Regosolic horizons observed.

4.2.1.6 Tombstone Valley

Tombstone Valley is a major south-facing tributary of the Elbow River (Figure 4.4). Located between the prominent peaks of Elpoca Mt. and Tombstone Mt., it contains an extensive alpine tundra near its headwaters below Mt.Jerram (Figure 4.5). Paleozoic limestones

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Figure 4.10 : The Paradise Valley study site. The arrow indicates the locations of the study lobes within this southward-facing headwater valley.

and dolomites dominate the local geology and a Wisconsin-age till mantles the valley floor (Jackson, 1977). Solifluction landforms are common throughout, as are prominent large-scale forms of patterned ground (Smith and Gardner, 1979).

The alpine tundra of Tombstone Valley slopes 2 km southward from around 2500 m asl at the valley headwall to approximately 2300 m asl at its lower end where it abuts a well-distinguished upper krummholtz zone. In an effort to characterize the general character of solifluction within this setting, three widely spaced turf-banked lobe sites were identified for study.

At the lowest elevation site, three lobes were identified (Lobes 2, 23, 24). Located on a southwest-facing segment of the valley floor at approximately 2310 m asl, these lobes are situated below a moist seepage zone dominated by *Salix barrattiana*. The lobes are composed of fine grained colluvium containing a few coarse fragments. Mantled by a *Salix arctica* dominated plant community, pedogenesis at these lobe sites is limited to Regosols. The annual snowcover usually lasts until mid June, after which the lobes become well-drained.

The second site in Tombstone Valley occurs on a gentle northeast-facing segment of the valley at approximately 2370 m asl. Two lobes (Lobes 1 and 25) were identified for study at this location (Figure 4.11). Both are composed of diamictons derived from the local ground moraine. Soil development at this site varies from Regosols to Brunisols. Because of its exposure, the site retains only a minimal winter snowcover. However, upslope nivation hollows contain late-lying snowbanks which drain across the site and cause short-term saturation. The dominant vegetation at the site is composed of communities of *Salix reticulata*, *Salix arctica* and/or *Phyllodoce aleutica*.

The final site within Tombstone Valley occurs near the valley headwall at 2476 m asl. Here, a well-vegetated solifluction sheet, composed of fine-grained colluvium, is overriding a poorly vegetated wind-scoured terrain. Along the edge of this sheet a prominent tongue of sediment has extended several meters beyond the main solifluction body. Designated Lobe 26, the front of this tongue is banked and protruding. It appears to lie along a main line of seepage

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Figure 4.11 : The Tombstone Valley study site. In the immediate foreground is Lobe 25, with a shovel midway up its tread surface providing scale. In the background is the abrupt, eastern, bedrock free-face of Mt.Elpoca.

originating from an upslope talus source.

4.2.1.7 Tyrwhitt Cirque

The Tyrwhitt Cirque study site is located on the northern limb of a large cirque basin below Mt.Tyrwhitt to the west of Highwood Summit (Figure 4.4). In 1980 a single turf-banked lobe (Lobe 22) was selected for study in well-vegetated colluvium, above the glacial limit, at 2412 m asl. Lobe 22 faces northwest just below the lip of a local break-in-slope. This lobe is dominated by a plant community of *Salix arctica* and *Carex nigricans*. It is composed of fine sediments characterized by Regosols.

4.3 The Mt.Allan Area

The Mt.Allan study area is situated within the Rocky Mountain Front Ranges at latitude 50° 57' N, longitude 115° 10' W (Figure 4.1). Part of Kananaskis Country, it includes within its borders the Marmot Creek Experimental Basin (Jeffrey, 1965). Mt.Allan (2805 m asl) overlooks the 50 km^2 study area (Figure 4.12). Topography throughout the area is steep (Figure 4.13), especially in the alpine where the slopes rise sharply to bedrock ridges (Stevenson, 1967). Drainage is via Wind Creek to the Bow River or down Ribbon and Marmot Creeks to the Kananaskis River.

The physiography of the area is controlled by a thrust plate of Mesozoic strata folded into a large overturned syncline (Crockford, 1949). Locally, where this syncline enters the Cascade Coal Basin, it bends and rises on its axis as the Mt.Allan Syncline (Sprang, et. al., 1981). Consequently, Kootenay strata composed of sandstones, shales, siltstones and coal underlie the area (Gibson, 1977), with the uppermost sandstone member forming the steep cliffs beneath Mt.Allan (Stevenson, 1967).

The geomorphic evolution of this study area remains poorly appreciated (c.f. Osborn and Jackson, 1974). During Wisconsin time valley glaciers extended to only 2200 m asl in the vicinity of Mt.Allan (Stevenson, 1967:10), with cirque glaciers filling the higher basins (Stalker, 1973). Deglaciation may have begun as early as 13,500 years BP (Jackson et. al.,

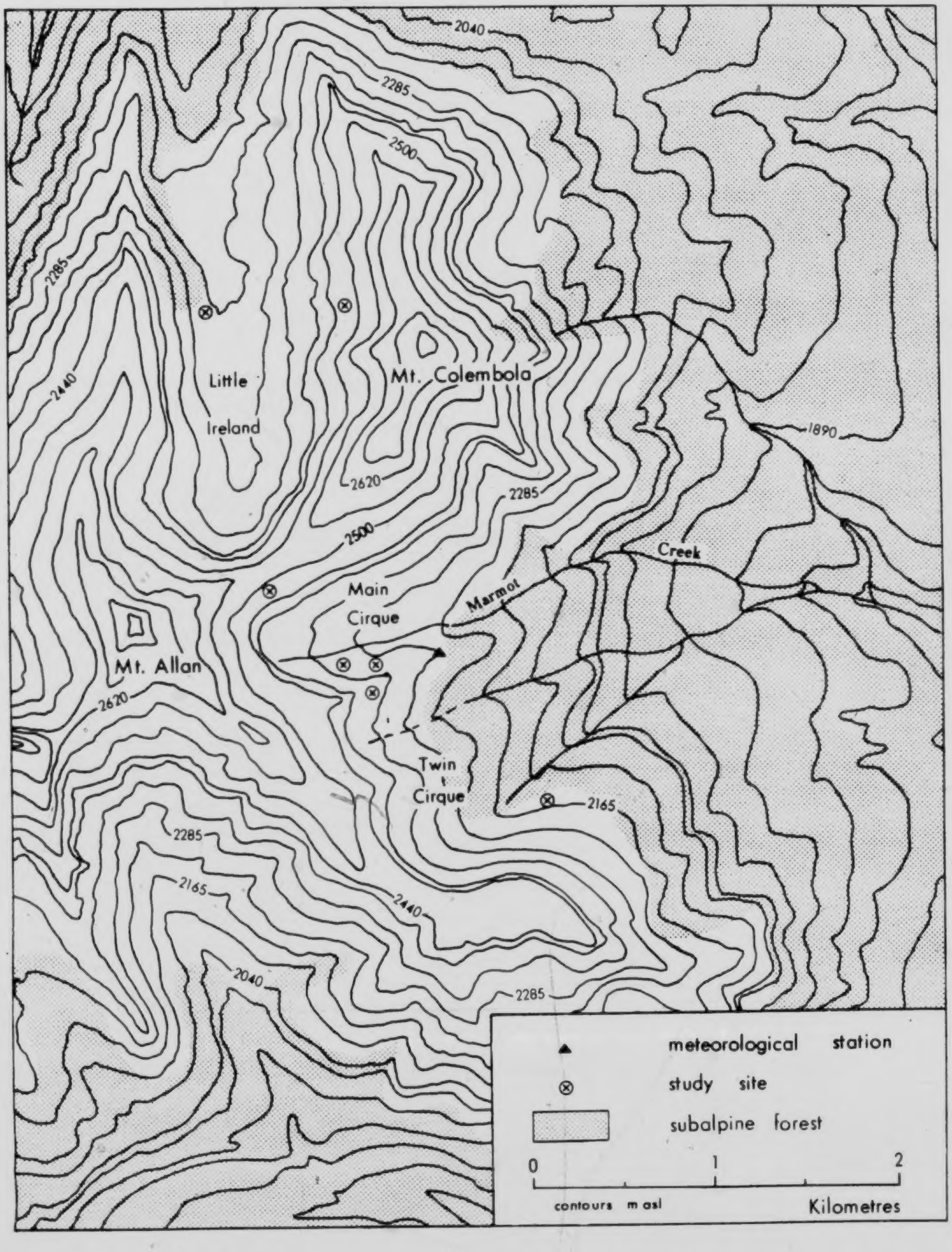
2040
2285
2500
2285
Little
Ireland
Mt. Colembola
2440
1890
2620
2285
2500
Creek
Marmot
Main
Cirque
Mt. Allan
2620
Twin
Cirque
2165
2285
2165
2440
2040
2285
▲ meteorological station
⊗ study site
▨ subalpine forest
0
1
2
contours m asl
Kilometres

Figure 4.12 : The Mt.Allan study area.

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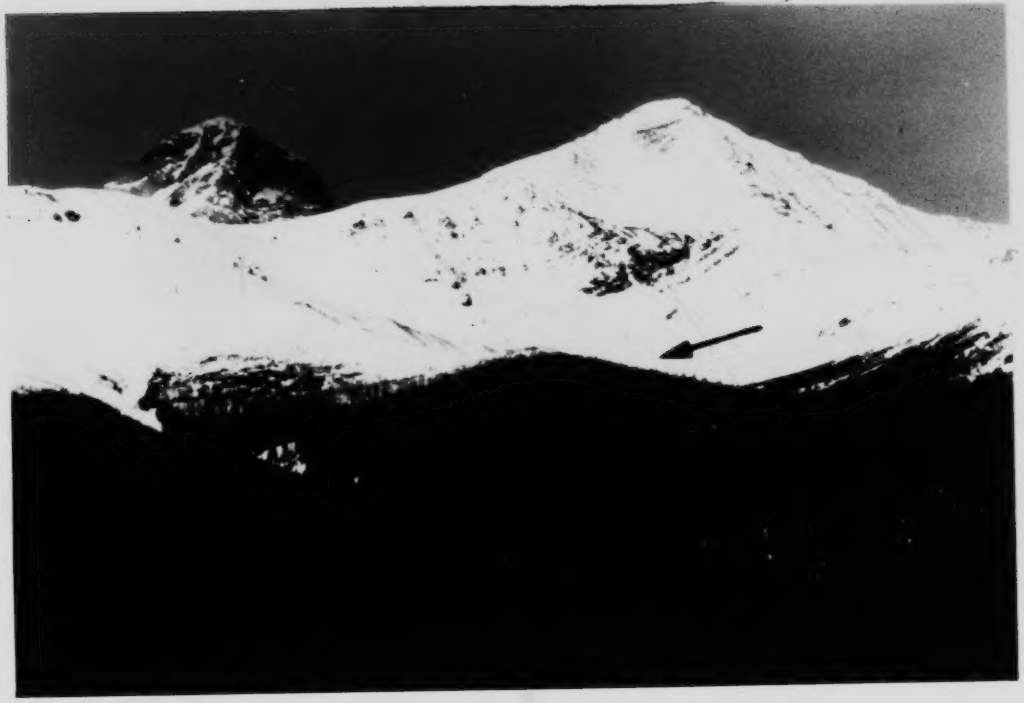

Figure 4.13 : A portion of the Mt.Allan study area. Mt.Allan is the prominent snow-covered peak, while Mt.Lougheed is visible behind the ridge. The arrow indicates the location of the Main Creek study site below the eastern face of Mt.Allan.

1981, 1982), but was complete by 10,400 years BP (MacDonald, 1980, 1982). Landscape changes within the Holocene period which followed were more subtle, with indications of only minor Neoglacial ice accumulations (Stalker, 1973:24).

The surficial geology of the Mt.Allan area reflects these events. In the alpine, cirque glaciers blanketed local slopes with a till predominated clay and silt, with sandstone and conglomerate boulders (Stevenson, 1967:20). Postglacial mass wasting has redistributed most of the till as colluvium (Beke, 1969). Containing admixtures of Mazama ash (Beke and Pawluk, 1971), soils developed on these deposits are characterized by Orthic and Cumulic Regosols (Beke, 1969). On cirque floors, where till remains *in situ*, Gleysolic and Regosolic soils (Beke, 1969) have formed in association with alpine meadows of ***Phyllodoce*** and ***Carex-Antennaria*** (Kirby and Ogilvie, 1969; Carroll, 1978).

The climate of the Mt. Allan area has varied throughout the Holocene. Paleoenvironmental records indicate that by 9395 years BP climatic conditions similar to today were established in this area (MacDonald, 1982:33). This period was followed by at least four episodes of severe climatic deterioration, from approximately 9000 to 8000 years BP, 5000 to 4500 years BP, 3000 to 2500 years BP and 1000 to 100 years BP (Jackson, et. al., 1981:59). In addition, a mid Holocene climatic amelioration, from 7500 years BP to shortly after 6600 years BP, was tentatively recognized by MacDonald (1980) in the palynological record of nearby Wedge Lake.

The contemporary climate of the Mt.Allan area varies considerably on a local basis (Environment Canada, 1974-1980). Mean annual air temperatures at the Twin One meteorological station (2285 m asl, Figure 4.10) average -0.8° C (Table 4.4). The mean summer temperature (May to September) is below 6.3° C, while mean January temperatures are -11.0° C. An extreme minimum temperature of -33.9° C (March 1, 1976) and a maximum temperature of 27.0° C (July 18, 1979) have been recorded. Although infrequent in July and August, ground frosts occur in all months of the year (Richards, 1981). The number of days with frost per year average 292, with frost alteration days peaking in the months of May (21

Table 4.4 : Mean monthly temperature (°C), Twin One, Mt. Allan area.

Month	Maximum	Average	Minimum
January	5.6	-11.3	-31.0
February	5.5	-9.2	-31.0
March	8.0	-8.4	-22.2
April	13.9	-1.9	-22.2
May	16.0	1.7	-10.0
June	24.4	6.4	-5.0
July	27.0	9.9	-2.0
August	25.0	7.8	-3.9
September	22.0	5.8	-7.8
October	18.0	1.3	-13.9
November	10.0	-5.5	-30.0
December	-0.1	-7.6	-28.3
annual mean		-1.6	

1. Environment Canada, 1974-1980, Compilation of Hydrometeorological Record, Marmot Creek Basin, Vol. 10-16, Water Survey of Canada, Calgary.

Table 4.5: Mean monthly precipitation (cm), Twin One, Mt.Allan Area.

Month	Maximum	average	Minimum
January	18.0	5.9	2.3
February	10.2	6.1	2.0
March	9.1	7.0	5.3
April	14.2	8.8	3.3
May	13.7	10.8	7.1
June	9.7	6.9	4.1
July	9.7	6.3	2.3
August	15.4	10.5	6.6
September	10.4	6.7	3.1
October	7.1	4.7	3.8
November	9.4	6.7	1.8
December	22.6	9.3	3.6
annual total		89.7	

1. Environment Canada, 1974-1980, Compilation of Hydrometerological Record, Marmot Creek Basin, Vol. 10-16, Water Survey of Canada, Calgary.

days) and October (17 days).

Mean annual precipitation at the Twin One station is 89.7 cm. Maximum precipitation occurs during May (10.8 cm), while minimum precipitation occurs in October (4.7 cm) (Table 4.5). Between 70 and 75 percent of the annual precipitation occurs as snow (Beke and Pawluk, 1971:665). However, much of this is locally redistributed by winter winds (Storr, 1973; Fisera, 1977) or is lost to evaporation (Golding, 1977; Louie, 1977) during the 25 to 30 chinooks per year (Longley, 1967; Janz and Storr, 1977) which sweep across this area.

4.3.1 Study Sites

The distribution and character of turf-banked solifluction lobes in the Mt.Allan area was initially noted in July, 1980. Following this, representative lobes at two principal sites and one subsidiary site were identified for study. Table 4.6 summarizes the general terrain and biophysical features at each of these sites. Detailed descriptions of the various sites and study lobe settings are presented in sections 4.3.1.1. to 4.3.1.3.

4.3.1.1 Little Ireland

Little Ireland is a deeply entrenched north-facing cirque valley abutting the northeast face of Mt.Allan (Figure 4.14). The cirque is floored by a disintegration moraine covered by alpine meadows and subalpine fir krummholtz (Carroll, 1978:71). On the steeply sloping valley walls an inverted timberline of subalpine fir and Englemann spruce grades upwards into *Carex* spp. meadows.

Solifluction landforms are common throughout this well-vegetated cirque and six turf-banked lobes were selected for study. Five of these lobes (Lobes 6, 7, 31, 32, 33) were located below Mt.Colembolla, mid-way up the moderately steep (20°) valley sidewall at approximately 2500 m asl. Located within a colluvial veneer composed of weathered Kootenay sandstone and shale, these lobes are situated below a conspicuous, longitudinal, nivation trench. They are composed primarily of fine-grained sediments, but contain local concentrations of cobbles and boulders around their perimeters. Despite the luxuriant *Carex* ssp. vegetation, soil

Table 4.6 : General geomorphic character of the Mt.Allan area study sites.

study sites;	altitude (m asl)	aspect	landfrom	bedrock lithology	genetic material	soils	vegetation (dominant)	study lobes
Little Ireland	2500 2600	W	valley side	Kootenay sandstone	colluvial	Regosols	sedge (*carex* ssp.)	6, 7, 31 32, 33
	2240	E	valley foot	Kootenay sandstone	colluvial	Regosols	dwarf shrub (*Salix* ssp.)	30
Main Cirque	2380 2434	N	valley foot	Kootenay sandstone	colluvial /glacial	Regosols	dwarf shrub (*Salix* ssp.)	5, 8, 9, 36 37, 38, 39
	2550	SE	valley side	Kootenay sandstone	colluvial	Regosols	dwarf shrub (*Salix* ssp.)	39, 40
Twin Cirque	2316	N	valley foot	Kootenay sandstone	colluvial	Regosols	dwarf shrub (*Salix* ssp.)	46

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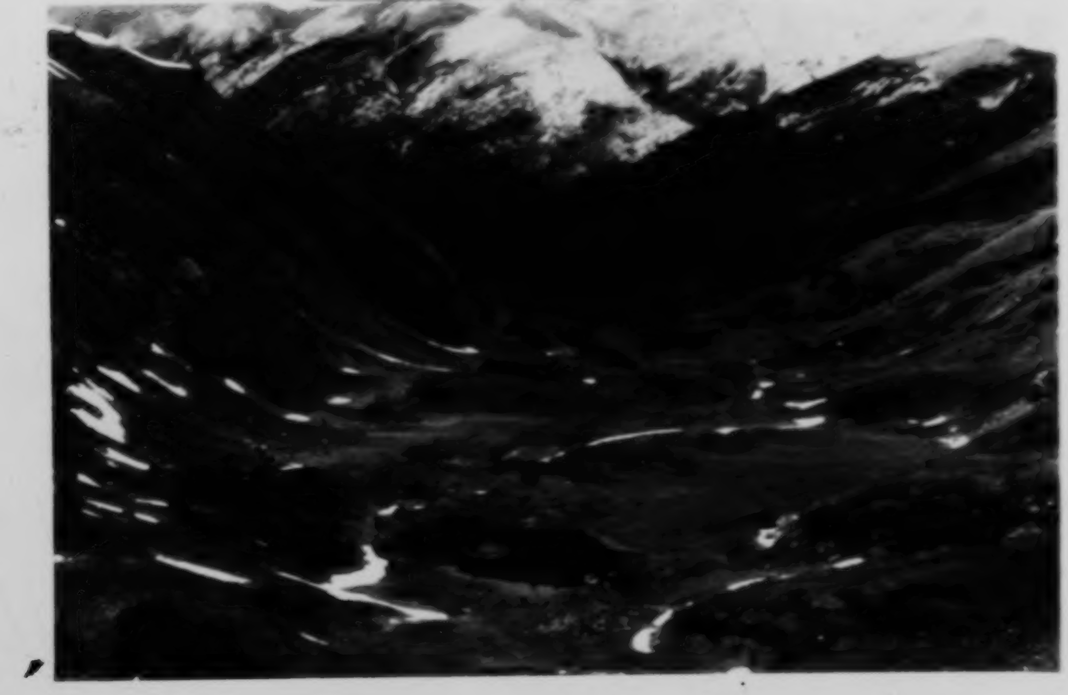

Figure 4.14 : The Little Ireland study site below the northern face of Mt.Allan. The lower arrow indicates the position of Lobe 30, while the position of the remaining lobes at this site is indicated by the second arrow.

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development is limited to Regosols.

One additional lobe, Lobe 30, was located at 2240 m asl on the footslope of the opposite, east-facing, valley wall. This tongue-shaped lobe is poorly vegetated except around its perimeters where a *Salix arctica* plant community blankets the protruding snout. The lobe is composed of talus fragments in a matrix of fine colluvium.

4.3.1.2 Main Cirque

The Main Cirque study site lies immediately to the east of Mt.Allan (Figure 4.15). It has an easterly aspect and contains tributary headwaters of Marmot Creek. In the upper alpine zone the low angle cirque floor is mantled by dissected till and postglacial rockfall deposits. The cirque walls are steep but covered by tundra vegetation. Large, steeply-banked solifluction lobes are common throughout the cirque, especially at the valley-side footslope where there is a prominent break-in-slope.

In total nine lobes were identified for study within Main Cirque. Seven of these lobes (Lobes 5, 8, 9, 36, 37, 38, 47) are positioned below the Twin One meteorological station along the strongly shaded (Ferguson, et. al., 1971; Storr, 1972) north-facing cirque wall between 2390 and 2434 m asl. While the seasonal snowcover lasts only until late June on this slope, frozen soil persists at relatively shallow depths throughout most of the summer (Richards, 1981).

These large tongue-shaped lobes (Figure 4.11) are composed of mixed till-colluvium (Beke, 1969) dominated by fine sediments but contain significant amounts of coarser cobbles and stones. Soil development varies in character at these sites but is Regosolic in nature. The vegetation cover at these sites is dominated by dwarf shrubs (*Salix arctica* and *Dryas octopetala*) and, in more shaded locations, a luxuriant moss cover.

Two additional study lobes (Lobes 39, 40) were located on the steep southeast-facing cirque backwall at 2550 m asl (Figure 4.10). Situated immediately below the well-weathered ridge crest, these lobes are composed primarily of fine-grained colluvial sediments. However, both have steep, well-vegetated, frontal banks dominated by large boulder fragments. An

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Figure 4.15 : The Main Cirque study site. The lobes under investigation are those visible in the centre of the photograph.

abundance of *Salix* ssp. at this location indicates it is a groundwater seepage zone.

4.3.1.3 Twin Cirque

The Twin Cirque site is located to the southeast of Mt.Allan (Figure 4.12). Solifluction within this cirque is restricted to the footslope of the north-facing cirque wall. A single lobe (Lobe 46) located at 2315 m asl was identified for long-term monitoring at this site. It is composed primarily of fine-grained colluvial material, with a large percentage of coarser material derived from the overhanging bedrock free-face. The vegetation cover at this site is dominated by *Salix* ssp., underlain by Regosols.

4.4 The Parkers Ridge Area

The Parkers Ridge study area is situated within the Main Ranges of the Alberta Rockies at latitude 52° 11', longitude 117° 06' (Figure 4.1). It is located within the Columbia Icefields region of northern Banff National Park.

Parkers Ridge is a prominent, windswept, alpine ridge extending eastwards from Mt. Athabasca for approximately 6 km (Figure 4.16). Its well rounded ridge summit has an average elevation near 2270 m asl (Figure 4.17). While slopes dip only moderately along the northern flank of the ridge, to the south they drop abruptly some 600 m to the valley of the Saskatchewan Glacier.

Structurally, Parkers Ridge sits on the north-plunging west limb of the Mount Wilson Syncline, overriden by the Simpson Pass thrust (Mountjoy and Geldsetzer, 1981). The local bedrock is Upper Devonian, composed primarily of dolomites and limestones but including minor units of sandstone or quartzites and argillaceous shales (Beylea and McLaren, 1964).

Glacial ice apparently enveloped Parkers Ridge several times during the late Pleistocene (Jennings, 1951; Baranowski and Henoch, 1978). However, radiocarbon evidence indicates deglaciation in the immediate area was complete by 9600 ± 300 years BP (Henoch, et. al., 1979; Kearney and Luckman, 1981). Subsequent readvances during the Holocene, for which there is evidence of several (Luckman, 1977; Luckman and Osborn, 1979: Leonard,1981), were

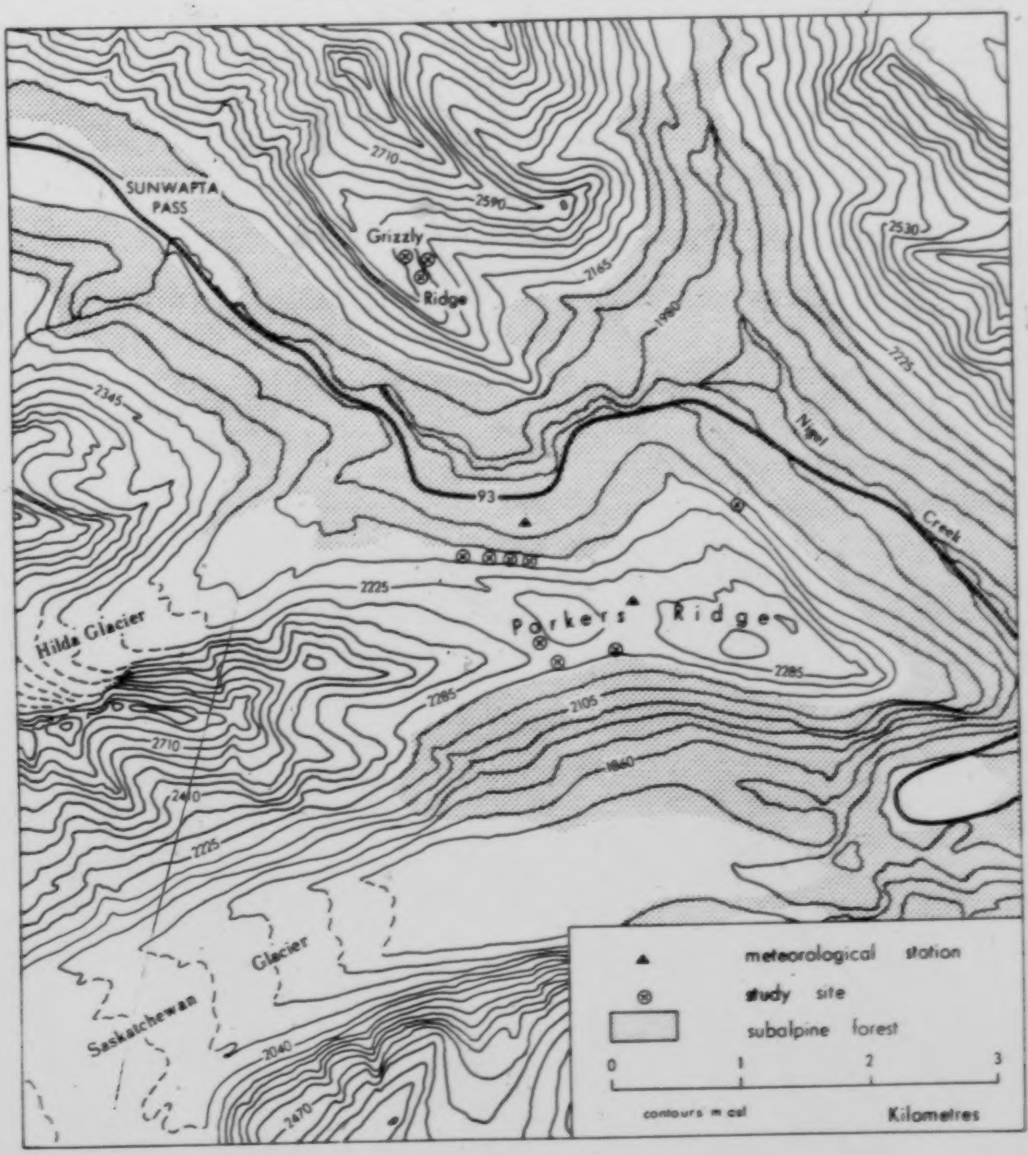
SUNWAPTA PASS
Grizzly
Ridge
2710
2590
2165
1980
2530
2225
Nigel
Creek
93
2345
2225
Parkers Ridge
Hilda Glacier
2285
2105
1860
2710
2410
2225
Saskatchewan
Glacier
2040
2470
meteorological station
study site
subalpine forest
0
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Figure 4.16 : The Parkers Ridge study site.

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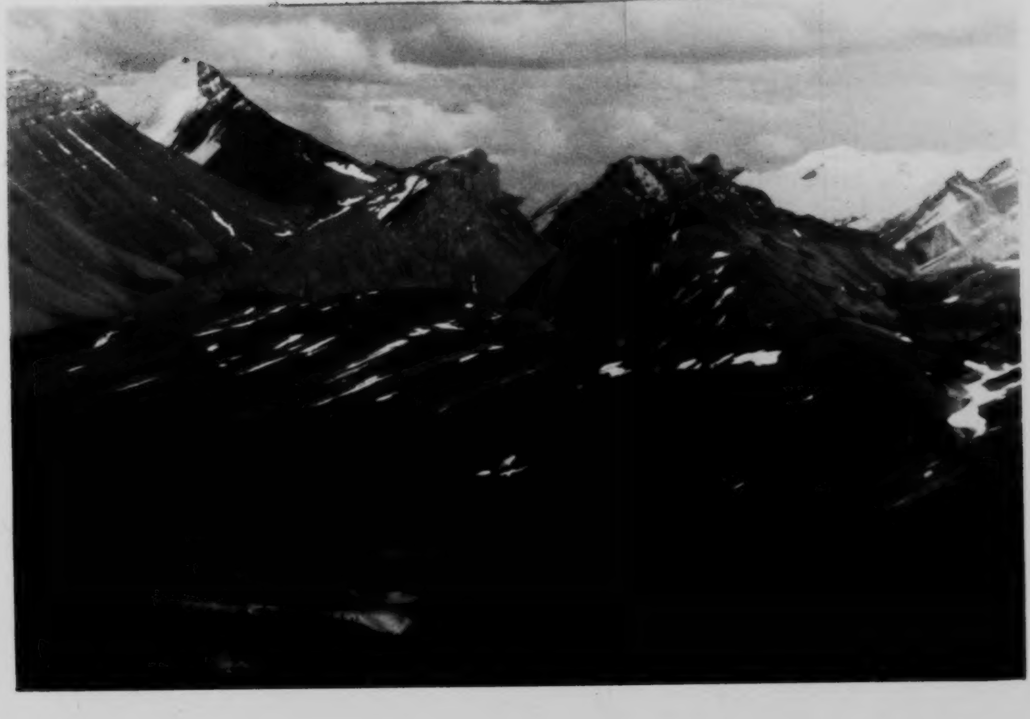

Figure 4.17 : The view south to Parkers Ridge from Wilcox Pass. The upper arrow indicates the site of Lobe 60, while the lower arrow points out the locations of Lobes 49-56.

relatively short episodes (Kearney, 1981; Kearney and Luckman, 1983a) and did not physically affect the ridge environment.

The retreat of glacial ice from Parkers Ridge left a veneer of calcareous till across the ridge summit (Holland and Coen, 1983). At higher elevations this has been colonized by alpine plants, while a spruce and fir subalpine forest has surrounded the ridge at lower elevations (Bowyer, 1977). Above treeline Eutric and Melanic Brunisols, and Orthic and Humic Regosols are common (Holland and Coen, 1982), while below both Brunisols and Podzolic soils dominate (C.Smith, 1979; Smith, et. al., 1981a, 1981b).

Paleoclimatic records in the vicinity of Parkers Ridge indicate that by 9700 years BP environmental conditions were similar to those experienced presently (Kearney, 1981; Kearney and Luckman, 1983b). Cooler conditions prevailed from 9000 to 7500 years BP, around 4800 years BP, from 3500 to 2800 years BP and from 1700 years BP to shortly before the present (Kearney and Luckman, 1981; Leonard, 1981). The climax of the warm, dry, Altithermal hiatus extended from 7500 to 5900 years BP in this region (Kearney, 1981). There is some indication that climates in the last 500 years are amongst the severest experienced in this region since early Holocene time (Bowyer, 1977; Kearney and Luckman, 1983a, 1983b).

The present climate of the Parkers Ridge area is much less continental than that experienced by the other two Front Range sites (Janz and Storr, 1977). On the ridge crest air temperatures (May to September) average -0.6°C, while the mean January temperature is -14.1°C (Table 4.7). Extreme temperatures on the ridge range from -36.0°C (December 30, 1978) to 25.5°C (August 26, 1981). The number of days with frost per year averages 269, with frost alteration days peaking in May (27 days) and October (23 days).

Mean annual precipitation (Table 4.8) in the vicinity of Parkers Ridge averages 642 mm (Parkers Ridge, 2267 m asl) to 744 mm (Nigel Creek, 2256 m asl). Maximum precipitation occurs in December (11.5 cm), the least amount falling during May (2.1 cm). Snow occurs in all months of the year, accounting for over 74 percent of the total annual precipitation (Janz and Storr, 1977). Winter snowfalls are quickly redistributed, with average accumulations

Table 4.7 : Mean monthly temperature (°C), Parkers Ridge.

Month	Maximum	Average	Minimum
January	5.0	-14.1	-36.0
February	4.5	-9.6	-34.0
March	10.0	-6.7	-30.0
April	15.0	-2.1	-24.0
May	17.0	3.7	-12.0
June	14.5	5.4	-3.0
July	20.0	8.6	-4.0
August	25.5	11.7	-1.0
September	22.0	6.0	-7.0
October	17.0	0.2	-16.5
November	8.0	-7.5	-31.5
December	6.0	-11.6	-36.0
annual mean		-1.3	

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1. Environment Canada, 1978-1982, Monthly Record Meteorological Observations in Western Canada, Vol. 63-67, Atmospheric Environment Services, Downsview.

Table 4.8 : Mean monthly precipitation (cm), Parkers Ridge.

Month	Maximum	Average	Minimum
January	7.6	3.9	0.7
February	16.6	10.1	1.1
March	10.3	6.6	4.0
April	9.9	5.6	2.4
May	3.0	2.1	0.7
June	3.9	4.0	4.0
July	10.4	3.7	3.7
August	3.4	3.4	3.4
September	5.8	4.3	2.9
October	5.1	4.2	3.5
November	11.5	5.0	1.3
December	19.8	11.5	5.0
annual total		64.2	

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1. Environment Canada, 1978-1982, Monthly Record Meteorological Observations in Western Canada, Vol. 63-67, Atmospheric Environment Services, Downsview.

ranging from 15.6 cm on the ridge crest to 89.0 cm in the subalpine forest immediately below (Harris and Brown, 1982:66).

4.4.1 Study Sites

Solifluction lobes in the vicinity of Parkers Ridge were initially examined in July of 1981. Following this investigation 15 turf-banked lobes were identified for long-term study within one principal study site and one subsidiary site. The general terrain and biophysical features of these sites are summarized in Table 4.9 . Detailed descriptions of each site are presented within sections 4.4.1.1. to 4.4.1.2.

4.4.1.1 Grizzly Ridge

The Grizzly Ridge study site is situated across the valley from Parkers Ridge on an east-facing alpine tundra slope at 2275 m asl (Figure 4.16). Located above a prominent lateral moraine, the site consists of a veneer of colluvial sediments overlying a moderately dipping bedrock ridge composed of Devonian limestones. The site is a location of ground water discharge, as evidenced by prominent *Salix barrattiana* dominated seepage zones, and early-season snow release. A number of well-vegetated lobes are situated downslope of these moisture sources within the local krummholtz ecotone.

Three turf-banked lobes (Lobes 57, 58, 59) were distinguished for study at this site. Composed largely of fine-grained sediments and only a few coarse fragments, these lobes are covered by dense mats of *Dryas octopetala*. Soil development at these study lobes is limited to a turfy upper horizon.

4.4.1.2 Parkers Ridge

In order to characterize the general nature of solifluction occurring on Parkers Ridge, three areas of turf-banked solifluction lobes were selected. A single lobe (Lobe 60) was identified immediately below a bedrock massif at 2039 m asl at the easternmost extremity of the ridge (Figure 4.16). Located just above the local treeline, this steeply-banked, tongue-shaped

Table 4.9 : General geomorphic character of the Parkers Ridge area study sites.

study sites	altitude (m asl)	aspect	landform	bedrock	genetic lithology	soils	vegetation (dominant)	study lobes
Grizzly Ridge	2275	E	valley side	Devonian limestone	colluvial	Regosols	dwarf shrub (*Salix* ssp.)	57, 58, 59
Parkers Ridge	2093	N	valley foot	Devonian limestone	colluvial	Regosols	dwarf shrub (*Salix* ssp.)	60
	2070	E	valley foot	Devonian limestone	glacial	Regosols	dwarf shrub *Salix* ssp./ ***Cassiope*** ssp.)	49, 50, 51, 52, 53, 54 55, 56
	2253 2290	SE-SW	interfluve	Devonian limestone	glacial	Regosols	dwarf shrub (*Salix* ssp.)	61, 62, 63

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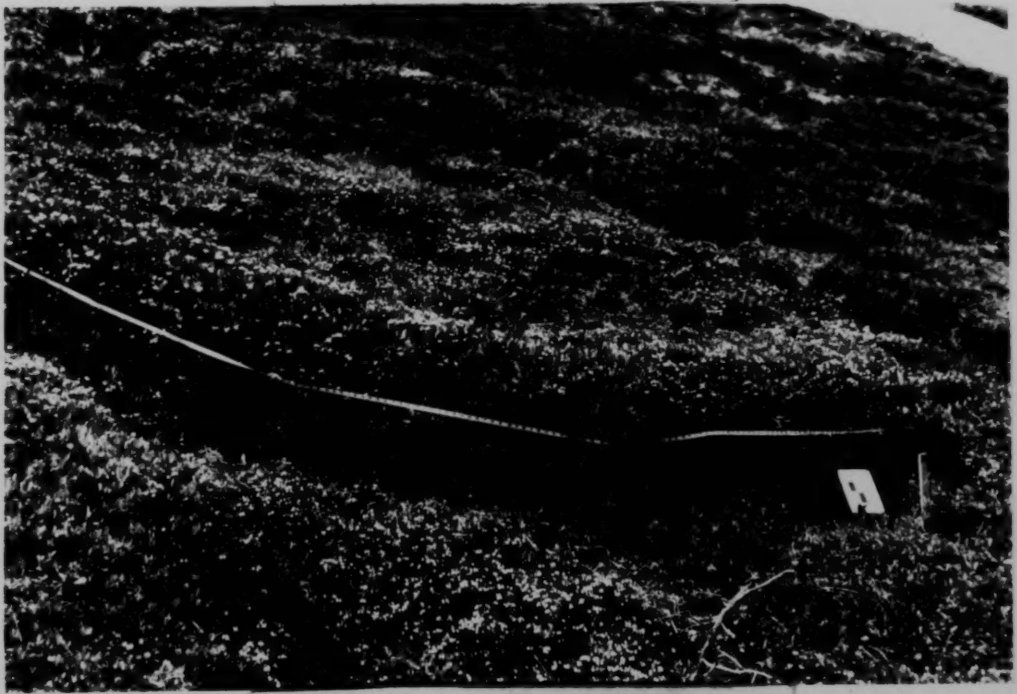

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Figure 4.18 : The setting of Lobe 49 located on the northeast-facing flank of Parkers Ridge.

lobe faces to the north and is composed of blocky sediments in a fine-grained matrix. It is situated within an area of groundwater resurgence which also experiences seasonal snow avalanching. Regosolic soils predominate locally, with *Salix barrattiana* dominating the local vegetation except around the lobe perimeter where *Salix arctica* is more common.

A second turf-banked lobe site was located immediately above treeline on the northern flank of Parkers Ridge at 2070 m asl (Figure 4.18). This moderately sloping subalpine ecotone is distinguished by a large number of coalescing and overlapping turf-banked lobe forms. Eight individual lobes (Lobes 49, 50, 51, 52, 53, 54, 55, 56) were identified for study at this location.

Located to the lee of the ridge summit, this site is one of significant winter snow accumulation and episodic snow avalanching. The upslope seasonal retreat of this snowcover commonly persists until late July and results in the release of significant quantities of meltwater which locally saturates the downslope solifluction deposits. These sediments are composed of a fine-grained till containing numerous cobbles and stones. Pedogenesis is limited to thinly displayed Regosols, largely because of the unstable nature of the site. The dominant vegetation cover is a *Salix* ssp./*Cassiope* ssp. plant community.

The third turf-banked lobe location identified at Parkers Ridge is situated on the ridge summit. While this interfluve slopes predominantly to the north, local slopes dip moderately in a variety of directions off a series of felsenmeer outcrops. Three lobes (Lobes 61, 62, 63), at various locations across the ridge summit, were singled out for detailed study (Figure 4.13). All are poorly vegetated, mainly by *Salix* ssp., and have only limited soil development.

Lobes 61 and 63, located at approximately 2260 m asl, overlook the Saskatchewan Glacier valley. Both have easterly aspects and are nourished by seasonally melting snowpacks. Lobe 61 is encroaching upon the local krummholtz zone, while Lobe 63 is moving over a bare soil surface. Lobe 62, located at 2290 m asl, faces to the southwest and is located at the base of a local felsenmeer outcrop (Figure 4.19).

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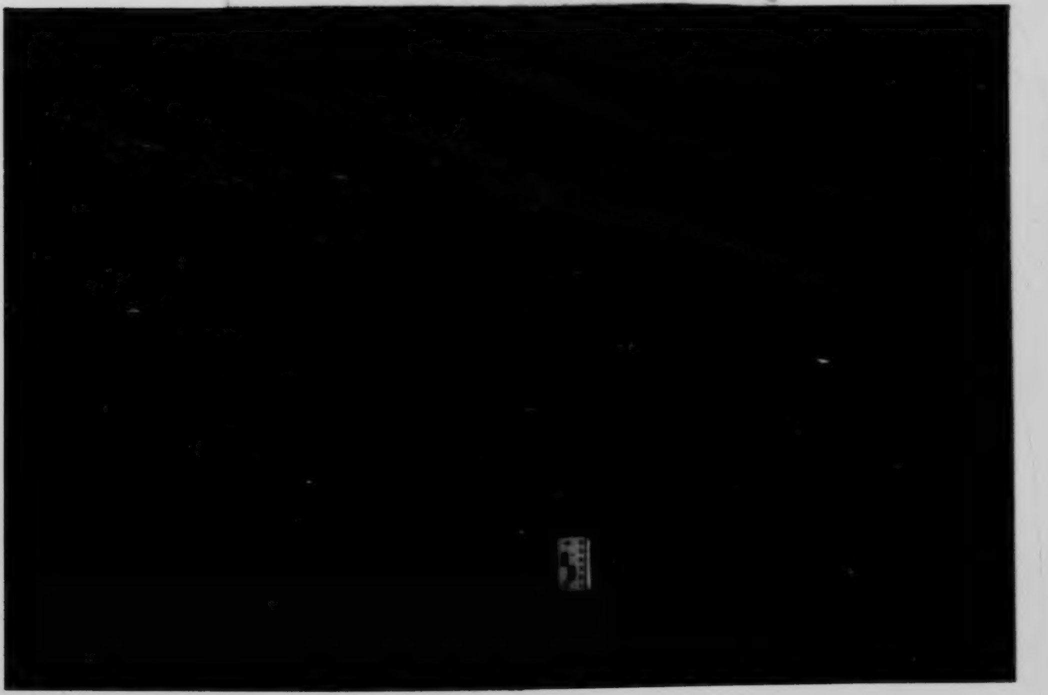


Figure 4.19 : The setting of Lobe 62 located on the interfluve summit of Parkers Ridge.

5. THE STUDY LOBES : GEOMORPHOLOGICAL CHARACTERISTICS

5.1 Introduction

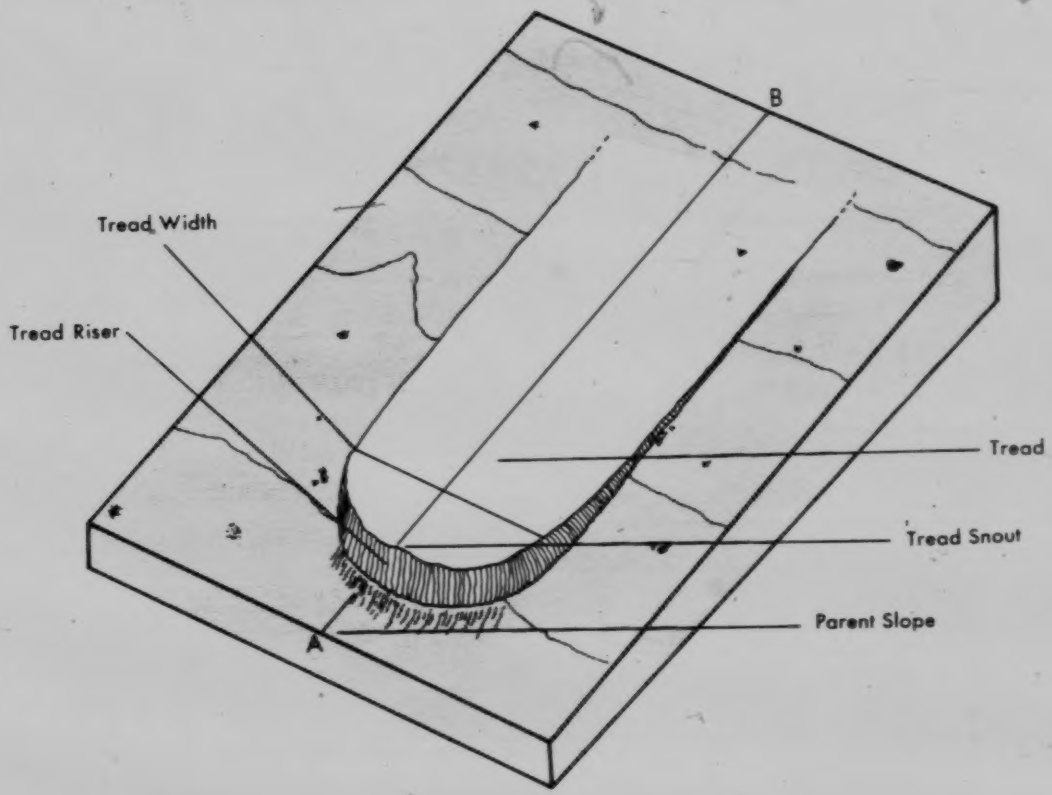
This chapter describes and analyzes the geomorphic nature of the 58 lobes selected to characterize solifluction within the Alberta Rocky Mountains. While this chapter is primarily designed to provide a basis for documenting the influence of these various characteristics on the contemporary movements discussed in Chapter 6, the results of these investigations in themselves provide insight into local solifluction morphogenesis.

In order to assess the characteristics of these different geomorphological parameters, several field and laboratory investigations were completed. These studies focused on establishing the morphological characteristics of these lobes, inventorying their locational parameters and detailing their sedimentological composition and geotechnical character. The following sections outline the methodologies utilized in these investigations and discuss the potential significance of these parameters to solifluction.

5.2 Morphological Analysis

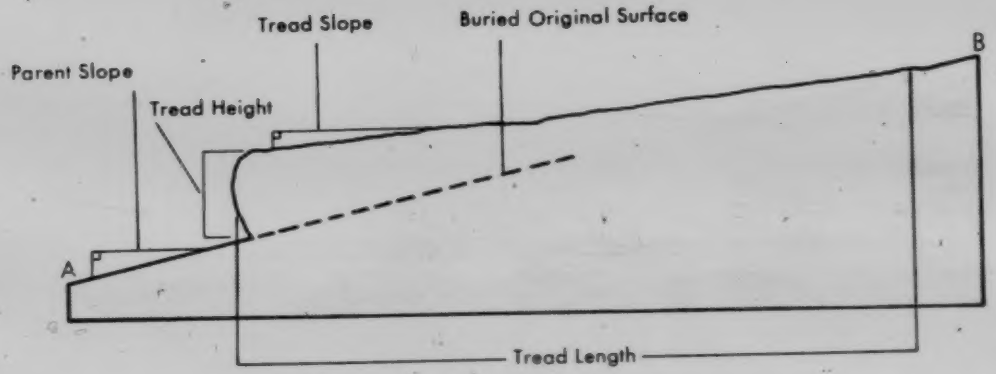
The morphology of individual landforms often reveals much about their origin (c.f. Owens, 1972, 1973; Crozier, 1973). In the case of solifluction landforms their morphometric characteristics must have a genetic underpinning (Hall, 1981; Heilbronn and Walton, 1984a). In the present study a number of distinctive morphometric elements were measured at each of the study lobe sites to ascertain their potential morphogenetic cause.

Several morphometric parameters were measured at each site: parent slope, tread height, tread length, tread angle and tread width (Figure 5.1). **Parent slope** refers to the local dip of the host slope across which the lobe is advancing; **tread height** describes the maximum depth of the lobe deposit along its frontal perimeter; **tread length** refers to the maximum length of the lobe along its central axis; **tread width** represents the maximum width of the lobe behind the snout; and **tread angle** describes the slope of the upper tread surface lying immediately



a) Solifluction Lobe Terminology

B
Tread Width
Tread Riser
Tread
Tread Snout
Parent Slope
A



b) Longitudinal Section

Tread Slope
Buried Original Surface
B
Parent Slope
Tread Height
A
Tread Length

Figure 5.1 : Different morphological components of turf-banked solifluction lobes.

upslope of the lobe snout. Each of these parameters was measured using either a steel tape (±0.5 cm) or a 1 m long slope profiler consisting of an Abney level (±0.5°) and an inclined board aligned downslope (Blong, 1972:185).

The second step in this morphological analysis consisted of, first of all, computing the average morphological character of the study lobes and, secondly, testing for morphogenetic links between the various morphometric parameters. The latter analysis was completed using correlation coefficients evaluated through the use of a t-test (Till, 1974).

5.2.1 Results

This morphological analysis suggested that the turf-banked lobes examined within the three study areas share many attributes. Indeed, there appears to be little morphological difference between the three areas, because all of the morphometric deviations fall within the inter-site standard deviations (Table 5.1). Based on these observations a *typical* turf-banked lobe within this area has a tread angle of 21.2°, a riser height of 0.41 m, a tread length of 2.56 m, a tread width of 3.88 m and incorporates an average of 8.08 m^3 of sediment.

Evaluation of the genetic relationships between each of these parameters suggests that there are several morphological combinations significant at the 0.05 level. The results of these correlation matrices are presented in Tables 5.2 and 5.3. Positive relationships appear between the angle of the tread slope and the parent slope, between the angle of the tread slope and the tread height, and between tread lengths and widths. Conversely, inverse relationships were indicated between the angle of the tread slope and the tread length, and between the parent slope and tread width.

These morphometric relationships imply that small (tread length x tread width) high-fronted lobes develop on steep slopes, large (tread length x tread width) low-fronted lobes on low angle slopes (Figure 5.2). In fact, from this analysis it is clear that the morphological character of individual lobes depends on the angle of the host slope. For example, as the parent slope increases so too does the tread slope, although at a slower rate. This necessitates an

Table 5.1 : Morphological measurements of study lobes.

	# sites	Mt.Rae	Mt.Allan	Parkers Ridge	Average
Average Slope Angle (°)	58	17.1	21.8	20.2	18.8
s.d.		5.5	5.3	7.6	6.1
Average Riser Height (m)	58	0.36	0.54	0.35	0.41
s.d.		0.12	0.22	0.09	0.16
Average Tread Length (m)	42	2.58	2.60	1.90	2.56
s.d.		1.98	2.07	1.76	1.89
Average Tread Angle (°)	58	17.6	28.5	20.5	21.2
s.d.		6.6	6.2	8.3	8.1
Average Tread Width (m)	31	4.22	4.41	2.64	3.88
s.d.		2.29	2.63	0.71	2.19

Table 5.2 : Correlation values for average morphological measurements.

	Parent Slope	Tread Height	Tread Length	Tread Slope	Tread Width	n
Parent Slope	1.00					58
Tread Height	0.18	1.00				58
Tread Length	-0.26	0.21	1.00			42
Tread Slope	0.63	0.35	-0.44	1.00		58
Tread Width	-0.34	0.10	0.35	-0.04	1.00	31

Table 5.3 : Correlation values accepted as significant at 0.05 level[1].

	Parent Slope	Tread Height	Tread Length	Tread Slope	Tread Width
Parent Slope					
Tread Height	no				
Tread Length	no	no			
Tread Slope	yes	yes	yes		
Tread Width	yes	no	yes	no	

1. accepted at 0.05 level of significance by t-test of r in Table 5.2.

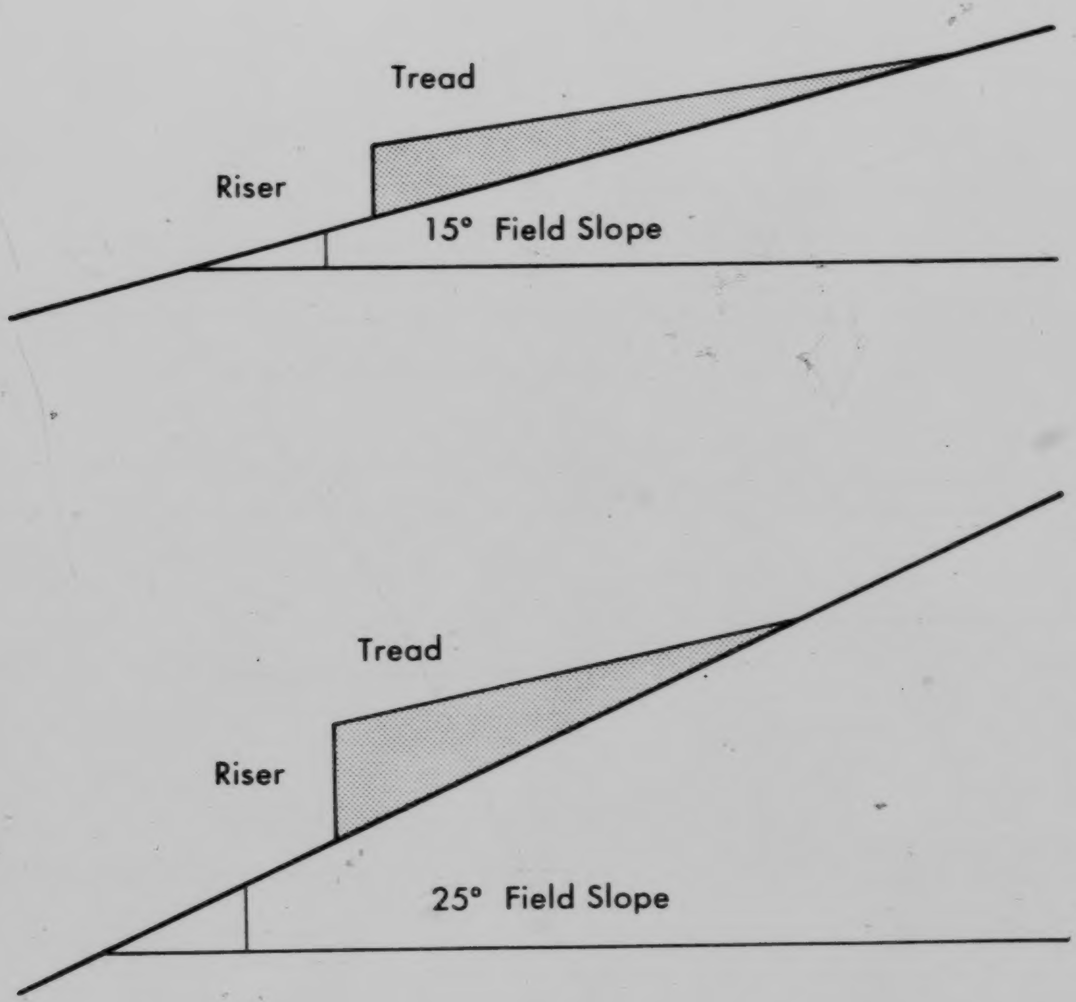

Tread
Riser
15° Field Slope
Tread
Riser
25° Field Slope

Figure 5.2 : Illustration of how riser height increases as a function of tread length and slope.

increase in the tread height while at the same time causing a decrease in both tread length and width (c.f. Hastenrath, 1973:163). The main reason for this complex relationship is the increasing confinement of solifluction to narrow, limited pathways on steeper slopes. On gentler slopes, where solifluction lobes commonly advance at slower rates (C. Harris, 1981a:114-116), they tend to involve larger quantities of sediment and, consequently, grow in size.

5.2.2 Discussion

Although a wide range of lobe sizes is indicated within the sample, correlation analysis confirms that all of the lobes are similar in form. Theoretically then, it should be possible to compare solifluction rates between the various lobes because they have all apparently experienced a similar morphodynamic form of concentrated solifluction. Specifically, this *typical* lobate form has been shown to result when the greatest rates of solifluction at a site are concentrated along a downslope oriented linear axis (c.f. Benedict, 1970:219; Price, 1973:243).

5.3 Locational Parameters

The rate and character of solifluction depends upon many environmental variables (C.Harris, 1981a). However, Price (1970a, 1973) found that several locational parameters did influence solifluction morphogenesis in the Yukon. Specifically, he discovered that lobes were best developed on southeast-facing slopes, where the greatest rates of movement occurred.

In order to appreciate the influence of location on solifluction activity within the Alberta Rockies, three parameters were established at each of the study lobes: altitude, aspect and gradient. **Altitude** was measured at the lobe snout using a Thommen Pocket Altimeter (±0.5 m asl); **aspect** was determined using a Brunton Compass (±1.0°) and described the orientation of the lobe; and **gradient** was measured using an Abney Level (±0.5°) and described the average site slope.

Since these study lobes were located at all of the major sites of solifluction activity discovered within each of the study areas, the results of this inventory provided a representative perspective of the areal differences in these three site parameters. This allowed these data to be used to examine the hypothesis that locational parameters are a controlling factor of solifluction movement in the Alberta Rockies.

5.3.1 Results

The results of these investigations are summarized in Table 5.4. The different study lobes were grouped according to their position within each study area to better illustrate the local ranges.

5.3.1.1 Altitude

Turf-banked solifluction lobes were discovered over a wide altitudinal range (2039 to 2600 m asl) within the field area (Table 5.4). However, the altitudinal distribution of these lobes varied between the three study areas (Figure 5.3). For instance, in the Mt.Rae and Mt.Allan areas lobes were found only above 2210 and 2240 m asl, where they have an average elevation of 2434 ± 87 m asl. In the Parkers Ridge area lobes were found at much lower elevations but extended only to approximately 2280 m asl and have an average elevation of 2147 ± 101 m asl.

This distributional pattern seems to reflect two things. First, the altitudinal lower boundary of turf-banked solifluction lobes within all three areas was defined by the upper limit of the treeline. As discussed previously in Chapter 3, treeline decreases in elevation northwards within the field area and it was not surprising to discover that lobes occurred at lower elevations in the Parkers Ridge area. Second, the fact that few of the surveyed lobes were discovered near the uppermost limits of these altitudinal solifluction zones (Table 5.4), suggests that the environmental conditions conducive to solifluction are far from ideal at these high-elevation sites.

Table 5.4 : Locational characteristics of study lobes.

Study Site	Lobe	Elevation m asl	Aspect degrees N	Gradient degrees
MT.RAE AREA				
Tombstone Valley	1	2370	307	14.0
Tombstone Valley	2	2300	204	15.0
K1	3	2455	298	13.5
Paradise Valley	4	2411	074	25.0
K2	10	2510	300	20.0
K2	11	2509	294	18.0
K2	12	2523	254	22.5
K2	13	2518	289	18.0
K2	14	2513	326	15.0
Highwood Ridge	15	2400	263	21.0
K2	21	2506	267	8.0
Tyrwhitt Cirque	22	2412	282	21.5
Tombstone Valley	23	2325	228	21.0
Tombstone Valley	24	2320	259	10.0
Tombstone Valley	25	2373	287	6.0
Tombstone Valley	26	2476	156	15.0
Paradise Valley	27	2397	074	25.0
Paradise Valley	28	2396	074	23.0
Paradise Valley	29	2399	060	14.0
Ptarmigan Ridge	34	2387	202	25.0
Ptarmigan Ridge	35	2388	185	19.5
K2	41	2511	281	15.5
Ptarmigan Ridge	42	2383	179	9.0
K2	43	2517	260	20.0
Ptarmigan Ridge	44	2390	191	20.5
Ptarmigan Ridge	45	2393	191	23.5
K1	48	2485	059	13.0
MT.ALLAN AREA				
Main Cirque	5	2390	345	27.0
Little Ireland	6	2500	226	20.0
Little Ireland	7	2495	236	17.0
Main Cirque	8	2386	345	25.0
Main Cirque	9	2386	336	19.0
Little Ireland	30	2240	071	20.5
Little Ireland	31	2600	261	12.5
Little Ireland	32	2492	260	19.5
Little Ireland	33	2490	261	22.0
Main Cirque	36	2388	334	25.0
Main Cirque	37	2389	345	22.0
Main Cirque	38	2434	060	25.0
Main Cirque	39	2550	140	20.5
Main Cirque	40	2552	141	33.0
Twin Cirque	46	2315	355	27.5
Main Cirque	47	2425	098	13.0
PARKERS RIDGE AREA				
Parkers Ridge	49	2065	003	24.0
Parkers Ridge	50	2070	000	19.0
Parkers Ridge	51	2073	010	22.0
Parkers Ridge	52	2073	020	26.0
Parkers Ridge	53	2071	027	20.0
Parkers Ridge	54	2068	000	32.0
Parkers Ridge	55	2070	007	28.5
Parkers Ridge	56	2071	005	13.0
Grizzly Ridge	57	2264	095	18.0
Grizzly Ridge	58	2275	080	18.5
Grizzly Ridge	59	2278	098	26.5
Parkers Ridge	60	2039	023	28.5
Parkers Ridge	61	2253	127	18.5
Parkers Ridge	62	2290	237	11.5
Parkers Ridge	63	2251	111	6.5

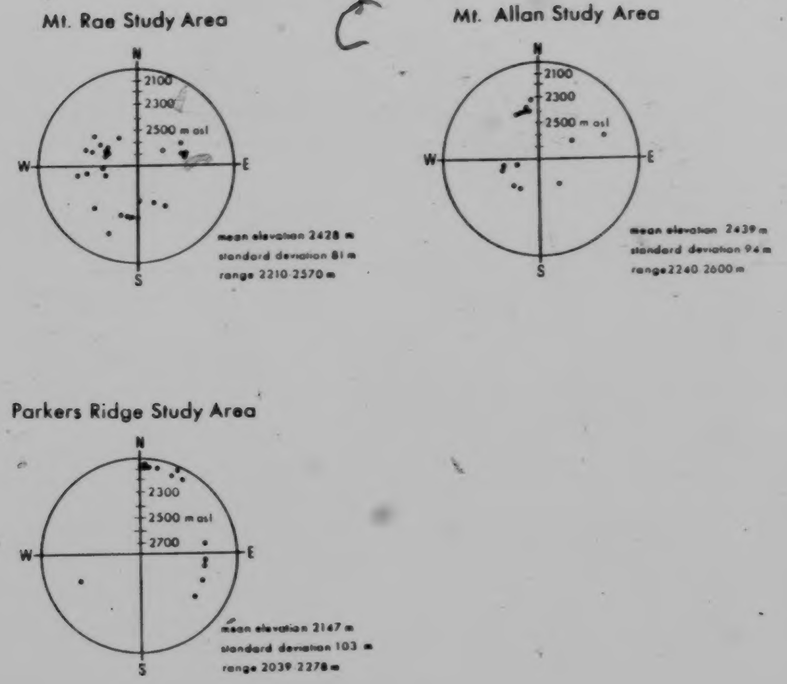


Figure 5.3 : Elevation and aspect of solifluction lobes in the three study areas.

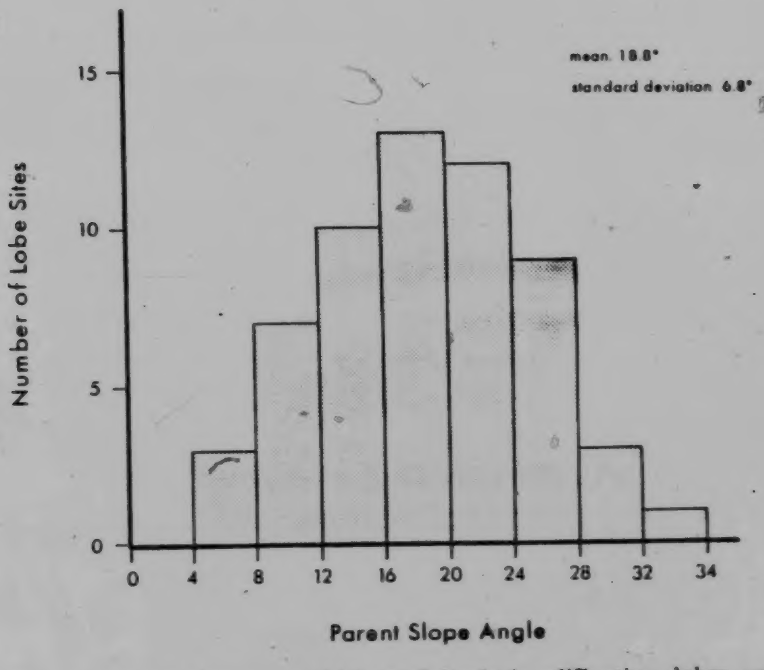


Figure 5.4 : Angle of parent slope on which turf-banked solifluction lobes are developed in the field area.

5.3.1.2 Aspect

Solifluction lobes within the three study areas illustrated distinct preferences for certain slopes (Table 5.4). In the Mt.Rae and Mt.Allan areas approximately 79 percent of the lobes were located on slopes which face predominantly northwest to south (Figure 5.3). Conversely, 93 percent of the lobes in the Parkers Ridge area occurred on north- to southeast-facing slopes (Figure 5.3).

These distribution patterns are a consequence of two factors. In the Mt.Rae and Mt.Allan areas, the southwest dip of the local Front Range sedimentary rocks means that there are a large number of moderate slopes with SW aspects. As a consequence, lobes are more frequent on slopes with these aspects, especially since many of the north- to east-facing slopes are characteristically scarp-faced. This influence of slope frequency is less important within the Parkers Ridge area, where the bedrock units are more or less horizontal. Instead the preference of solifluction lobes for northeast to easterly-facing slopes is probably influenced more by prevailing westerly winds, which build large winter snowbanks along protected slopes with easterly aspects. Melting of these snowpacks means that such slopes are wetter and more subject to solifluction (c.f. C.Harris, 1982:300). While this may explain the preference of solifluction lobes for northeast-facing slopes in the Parkers Ridge area, it should be recognized that the total number of lobes and sites examined within this area was relatively small.

5.3.1.3 Gradient

The lobes examined for this study were found at locations having slopes between 6° and 33° (Table 5.4). While these slopes appear to be normally distributed around a mean of 18.8° ± 6.8°, only a few lobes were discovered on slopes greater than 28° (Figure 5.4). The steepest host slopes were found in the Mt.Allan area (mean 21.8° ± 5.3°), while host slopes in the Mt.Rae area were among the most moderate (mean 17.1° ± 5.5°).

This contrast in slope gradients between the different study areas corresponded to variations in the topography at the various study sites. For instance, in the Mt.Allan area all of the solifluction sites identified were situated on or below relatively steep valley walls. In contrast, a number of the sites identified within the Mt.Rae and Parkers Ridge areas were found on low gradient ridge summits or valley floors.

5.3.2 Discussion

This investigation has suggested that solifluction mass wasting within the general field area was influenced by several site-specific factors. The spatial pattern of the lobes examined, indicated that both elevation and slope gradient combine to limit significant solifluction to moderately steep slopes close to the local treeline. The specific influence of slope aspect is uncertain, although it was recognized to be highly dependent upon local conditions. Interestingly, it can be concluded, from the normal distribution curve illustrated by Figure 5.4, that the results of these investigations should provide a representative picture of solifluction mass wasting on alpine slopes within the Alberta Rocky Mountains area.

5.4 Geotechnical Characteristics

Solifluction is favoured by sediments susceptible to ice segregation, heaving and flow (Benedict, 1976:61-62; C.Harris, 1981a:104-109). As a consequence, solifluction sediments tend to consist mainly of sand (45-50%) and silt (30-50%) having low clay (7-13%) contents (c.f. Graf, 1973:126). Such poorly sorted sediments generally lack frictional strength, have low liquid limits and limited plasticity (Washburn, 1967; De Ploey, 1972; C.Harris, 1977). These properties encourage slope instability and thus are important determinants of solifluction movement. Clearly, any areal variations in these physical properties offers a potential explanation for differential rates of solifluction.

To elucidate the character of solifluction sediments within the general field area, soil pits were dug within as many of the study lobes as possible. A total of 43 lobes were sampled (74 percent of the study sample), with at least two pits dug at each of the major study sites. Each pit was dug 1 m behind the lobe front and a bulk sample of sediment collected at one-half the lobe depth.

The physical properties of these sediments were determined using a variety of field and laboratory techniques. Volumetric estimates of the greater than 2.00 mm fraction were subjectively assessed in the field using the criteria presented by Day (1983:72). Particle size analysis of the less than 2.00 mm fraction followed standard procedures (American Society of Testing and Materials, 1981 : D 422-63), with dispersion achieved using sodium hexmetaphosphate. Determination of sand sizes (0.74 to 2.00 mm) was made by dry sieving, while fine grain grading (< 0.74 mm) was determined by the hydrometer method. The index properties of these sediments (liquid and plastic limits) were determined from samples split for grain size analysis (American Society for Testing and Materials. 1981 : D 423-66 and D-424-59). In several instances unit weight estimates were derived from multiple, near-surface, bulk density measurements made using a volumetric sampler in the field (McKeague, 1978 : 2.211).

5.4.1 Results

Solifluction sediments in the field area were discovered to be morphologically quite diverse. For the most part pedogenic activity within these sediments was limited in character, although locally effective edaphic factors had promoted limited soil formation at some sites. Despite this, the physical nature of these sediments proved to be remarkably similar. The results of these investigations are summarized in Table 5.5. Details of specific physical properties and their probable influence on solifluction are presented in the following sections.

5.4.1.1 Texture

Solifluction deposits in the three study areas consist predominantly of silty to stony loams (Table 5.5). While the data indicate a wide variation in textural classes (Figure 5.5), the less than 2.0 mm fraction is dominated by sand (mean 49.7 ± 11.5 percent) or silt (mean 41.0 ± 11.9 percent), with clay accounting for only a small percent (mean 10.1 ± 6.2 percent) of the total (Table 5.6). The relatively few coarse fragments, generally accounting for less than 15 percent by volume, in this fine matrix consisted of angular colluvial cobbles or glacial stones.

Table 5.5 : Physical properties of solifluction sediments.

Lobe	PARTICLE SIZE				BULK DENSITY	INDEX LIMITS		
	greater[1] 2 mm	less[2] 2 mm sand	silt	clay	($\mathrm{kN/m^3}$)	Liquid Limit (%)	Plastic Limit (%)	Plasticity Index (%)
MT.RAE AREA								
1	1	40	59	1		25	16	9
3	2	65	32	3		29	29	NP[4]
4	1	65	38	5		28	28	NP
10	2	55	45	3	7.98	32	28[5]	5[6]
11	2	54	44	2	8.22	34	29[5]	5[6]
12	2	56	32	12	7.39	29	25	14
13	2	57	43	10	4.88	34	24	10
14	2	44	52	4	6.19	42	33	9
15	1	23	58	22		34	32	2
21	2	47	48	5	10.11	32	27[5]	5[6]
22	2	55	38	7				
23	2	43	48	9		23	18[5]	5[6]
24	2	37	59	4		25	18	7
25	2	45	44	11		28	16	12
26	1	22	69	9		37	20	17
28	1	44	44	12		27	16	9
29	1	44	56	5		30	15	15
34	1	34	62	4		27	21	6
35	1	38	56	6		25	20[5]	5[6]
41	1	58	28	14	8.60	35	17	17
45	2	38	60	2		24	19[5]	5[6]
MT.ALLAN AREA								
6	1	64	27	9		22	20	2
7	1	65	23	12		23	23	NP
9	1	40	37	23		27	16	11
30	1	45	45	10		25	11	14
31	1	69	22	9		32	32	NP
32	1	61	38	1		27	27	NP
33	1	57	31	12		25	15	10
37	1	51	32	17		26	14	12
38	1	49	29	22		24	13	11
PARKERS RIDGE AREA								
50	2	45	27	28	13.45	22	11	11
51	2	51	36	13	10.68	23	12	11
52	2	64	21	15	11.21	22	14	8
53	2	50	38	12	12.03	21	10	11
54	2	58	30	12	9.80	30	21	9
55	2	54	33	13	11.86	20	11	9
56	2	34	48	18	12.89	27	21	6
57	1	40	49	11		26	nd[7]	nd
58	1	57	33	10		25	nd	nd
59	1	58	33	9		26	nd	nd
61	1	44	44	12	7.86	24	17	7
62	2	71	29	5	14.74	8	8	NP
63	2	48	40	12	13.08	25	10	15

1. after Day(1983:72): greater 2.00 mm where 1=less 15% volume, 2=15-35% volume, 3=35-60% volume.
2. percentage of the less than 2.00 mm fraction.
3. dry unit weight.
4. NP = nonplastic.
5. minimum estimate.
6. maximum estimate.
7. nd = no data.

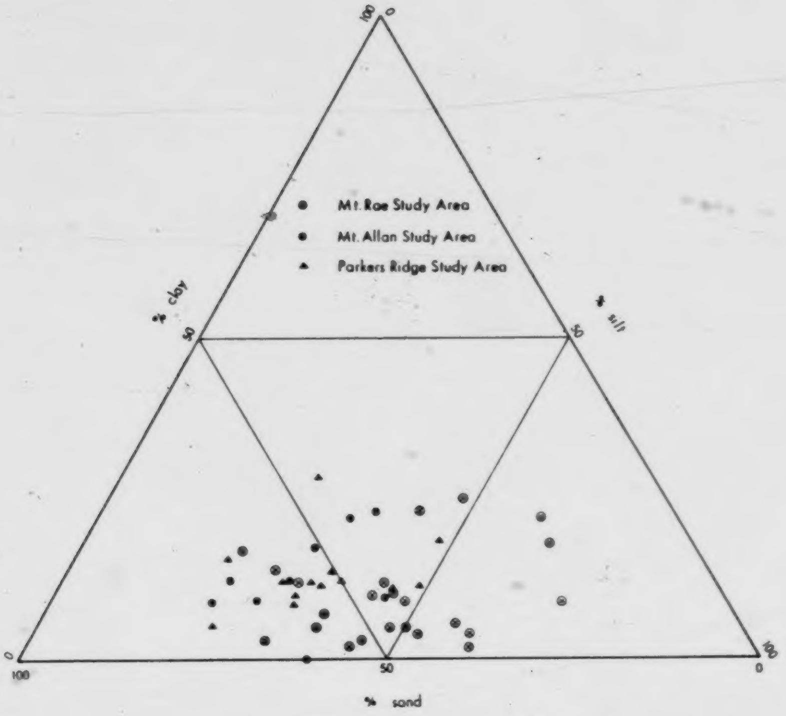


Figure 5.5 : Textural triangle of particles smaller than 2.00 mm.

Table 5.6 : Mean clay/silt/sand percentages.

		n	clay	silt	sand
Mt.Rae		21	7.1	48.3	45.9
	s.d.		5.1	11.1	11.9
Mt.Allan		9	12.8	31.5	55.7
	s.d.		6.9	7.5	9.9
Parkers Ridge		13	13.1	33.2	48.0
	s.d.		5.4	11.6	17.3
Average		43	11.1	41.0	49.7
	s.d.		6.2	11.9	11.5

Particle size data for lobes in the Mt.Rae area are summarized in Table 5.6. Textural envelopes of the less than 2.00 mm fraction indicate there is quite a range of classes within this area (Figure 5.6a), though very fine sands and silts (median 0.05 mm) dominate. The amount of clay tends to be quite low (mean 7.1 percent), with only one site (Lobe 15) consisting of more than 20 percent clay.

Granulometric data from the Mt.Allan lobes describe sediment which is much less disparate (Table 5.5). The less than 2.00 mm fraction has a narrower range (Figure 5.6b), but a coarser median particle size (0.15 mm), with medium to coarse sands dominating. Average clay contents are slightly higher, but cover a range similar to those in the Mt.Rae area.

Parkers Ridge sediments consist of stony to nonstony loams and silt loams (Table 5.5). Very fine sands dominate the less than 2.00 mm fraction (median 0.07 mm), with silts comprising a noticeably lower percentage (Figure 5.6c). The average clay contents (mean 13.1 ± 5.4 percent) were among the the highest encountered.

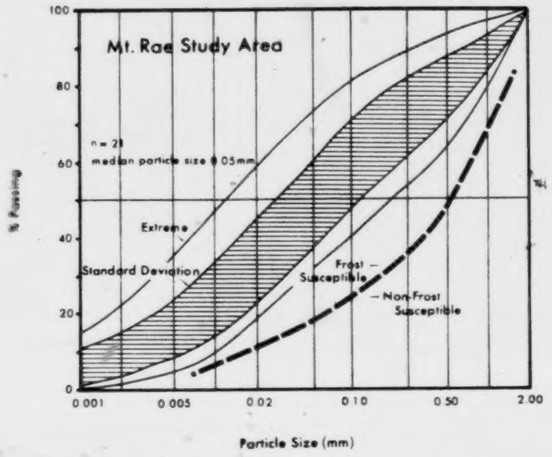
Apart from a few atypical examples, the sediment from all of the lobes is texturally similar. Because of this, it seems unlikely that textural variations can be used to account for any regional differences in solifluction rates which might occur within the field area. This point was emphasized by an examination of the frost susceptibility of these solifluction sediments.

Frost Susceptibility

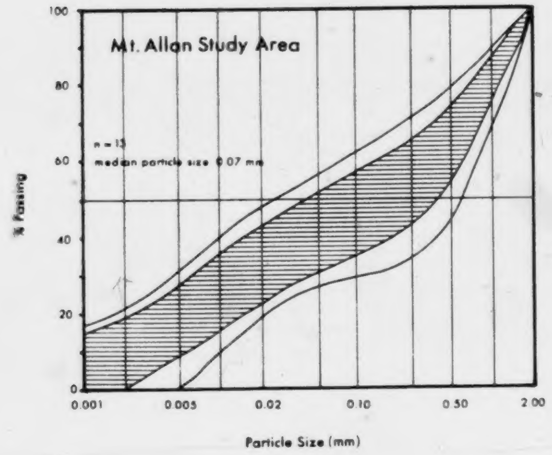
Sediments which are referred to as frost susceptible experience either destructive frost heaving or substantial thaw weakening (Anderson, et. al., 1978:81). While a number of techniques have been developed to determine the frost susceptibility of a sediment (c.f. Chamberlain, 1981), Johnston, et. al., (1981) concluded that evaluations based on grain size still provide a valid basis for its determination and classification. Thus, coarse to medium sands are generally considered to be non-frost susceptible, while fine sands to clays all appear to be frost susceptible (Beskow, 1935).

In this study, frost susceptibility was initially examined using the empirical criteria presented by Beskow (1935). Examination of the textural curves in Figure 5.6 indicated that

a) Mt. Rae Textural Envelope



b) Mt. Allan Textural Envelope



c) Parkers Ridge Textural Envelope

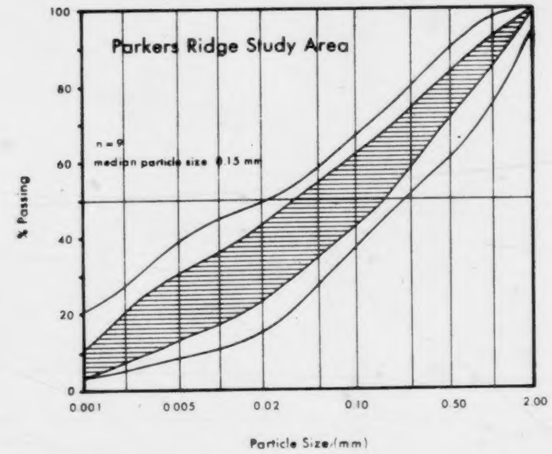


Figure 5.6 : Textural envelopes of solifluction sediments (less 2.00 mm fraction).

virtually all of the material sampled could be considered frost susceptible. It was not clear, however, from this analysis to what degree this property varied among the different study sites.

One approach to this problem is to estimate their relative susceptibility. This was accomplished in the present study by evaluation of a simple surrogate, the sand content of the less than 2.00 mm fraction. Caine (1978b:18) has indicated that this property is inversely related to frost susceptibility as defined by Beskow (1935).

Spatially, the sand contents of solifluction sediments found within the three study areas appear to be similar (Table 5.7). In fact, one-way analysis of variance testing revealed that there are no significant differences in sand contents either within or between the three study areas (Table 5.8). In view of these relationships, its seems equally unlikely that any spatial variations in solifluction activity which might be recorded within the field area are resultant from differential frost susceptibility.

5.4.1.2 Index Properties

The behavior of fine grained solifluction sediments depends upon their consistency state (De Ploey, 1972). While each consistency mode is conditioned by the instantaneous moisture content of the sediment, their relative cohesion is ultimately dependent upon the engineering properties of liquid and plastic limit. Washburn (1967:104-108) for instance, views the **liquid limit**, the water content above which the soil behaves as viscous liquid (Bowles, 1979:33), as an essential parameter for gelifluction. He also argues that the **plastic limit**, the water content below which the soil no longer behaves as a plastic material (Bowles, 1979:34), represents the lower moisture boundary necessary for solifluction to occur (Washburn, 1979:204). Thus, it can be assumed that spatial differences in these index properties would be an important factor of differential solifluction.

In order to determine the relative importance of these geotechnical limits to solifluction within the field area, laboratory techniques were used to document their specific properties at the various study lobes. Because the susceptibility of these sediments to flow varies with their *activity* (Young, 1972:77), where possible their **plasticity index** (liquid limit minus plastic limit)

Table 5.7 : Solifluction sediment (finer than 2.00 mm fraction) sand content(%).

study site	n	mean	s.d.
MT.RAE AREA			
K1	2	59.0	15.6
K2	7	56.1	5.8
Paradise Valley	3	52.0	7.0
Ptarmigan Ridge	2	42.0	8.5
Tombstone V.	6	57.7	11.4
MT.ALLAN AREA			
Little Ireland	5	56.0	10.0
Main Cirque	4	61.0	10.0
PARKERS RIDGE AREA			
Grizzly Ridge	7	54.6	10.1
L. Parkers	3	54.7	8.1
U. Parkers	3	56.0	16.1

Table 5.8 : One-way analysis of variance of sand contents in the less than 2.00 mm fraction.

	SS	df	MS	F-value	Significance
MT.RAE AREA					
Between	379.8	4	95.0		
Within	1096.2	18	60.9	1.56	NS[1]
Total	1476.0	22			
MT.ALLAN AREA					
Between	281.3	1	281.3		
Within	3243.7	9	360.4	0.78	NS
Total	3525.0	10			
PARKERS RIDGE AREA					
Between	3.9	2	2.0		
Within	1118.1	12	93.2	0.02	NS
Total	1122.0	14			
FIELD AREA					
Between	88.0	2	44.0		
Within	4136.8	40	103.4	0.43	NS
Total	4224.8	42			

1. NS = not significant

was determined.

Observations

The liquid limits of solifluction sediments examined in this study were low, averaging just 28 ± 9.4 percent (Table 5.5). Sediments in the Mt.Rae area had among the highest values (mean 33 ± 11.1 percent), while those from the Parkers Ridge area had among the lowest (mean 23 ± 5.3 percent). The liquid limits of solifluction sediments in the Mt.Allan area averaged 25.9 ± 2.9 percent.

The plastic limits of these sediments were similarly quite low, averaging less than 18.5 ± 6.2 percent at each of the study lobes (Table 5.5). The plastic limits of sediments within the Mt.Allan and Parkers Ridge study areas had among the lowest values, with a mean of 14.8 ± 3.1 percent and 12.0 ±5.2 percent respectively. Sediments within the Mt.Rae area have slightly greater plastic limit values, averaging 21.9 ± 5.8 percent.

Most of the sediments examined had narrow plasticity ranges, with 92 percent have a plasticity index of less than 12 percent (Table 5.5). At six of the lobe sites (Lobes 3, 4, 7, 31, 32, 62) the sediments were classified as non-plastic. This characteristic corresponds to locations of high sand and low clay ratios in the less than 2.00 mm fraction.

Discussion

In general, these index properties of low liquid limits and low plastic limits suggest that solifluction sediments within the field area are sensitive to relatively low field moisture contents (c.f. Everett, 1967; Fritze, 1971). Further, they indicate that the transitional phase between plastic and liquid flow is influenced by minor soil moistures fluctuations. It needs to be pointed out, however, that both Jahn (1961) and Harris (1977) have observed situations were moisture contents well above the liquid limit did not result in solifluction. Thus, these properties alone cannot always be used to distinguish soil equilibrium.

Despite slight areal differences in these index properties, there do not appear to be any major character variations which might be attributed to regional pecularities. Rather, the variations which did appear result from the differing local qualities of the sediment tested. Thus in the present discussion the importance of these index properties relates more to the character of local solifluction activity than to any regional variations in solifluction movement.

5.4.1.3 Unit Weights

The shear strengths of solifluction sediments are affected by their unit weights (c.f. Hutchinson, 1974; Derbyshire, 1977). Because this geotechnical property normally exhibits wide areal variations, it might be expected to differentially influence solifluction activity. In order to explore this hypothesis unit weights of near-surface solifluction sediments (< 20.0 cm) were derived for several study sites located within the three areas (Table 5.5).

Observations

Unit weight determinations made at the K2 site in the Mt.Rae area resulted in an assessed value averaging 7.62 ±1.70 kN/m^3. At the Parkers Ridge site unit weights averaged 11.76 ± 1.98 kN/m^3. Unfortunately, no attempt was made to document unit weights within the Mt.Allan area, although the value of 7.45 kN/m^3 established by Beke (1969) provides a useful estimate of conditions above treeline in Main Cirque.

Discussion

Table 5.9 compares these unit weight determinations with examples from other solifluction sites. While conditions at Parkers Ridge appear similar to those observed elsewhere, it appears density conditions at both the K2 site and in Main Cirque may be somewhat atypical. Empirically, it appears that the loose structure and composition of the Cretaceous-based colluvium at both sites is responsible for these reduced unit weights. While this discovery obviously requires further investigation, this study does confirm that areal difference in unit weight properties may be a controlling factor of local variations in solifluction activity (c.f. McRoberts, 1978).

Table 5.9 : Unit Weights[1].

location	texture	mean dry unit weight		source
		kg/m^3	kN/m^3	
MT.RAE AREA				
K2[2]	sandy-silt	777	7.6	this study
MT.ALLAN AREA				
Main Cirque	silty-sand	760	7.5	Beke (1969)
PARKERS RIDGE AREA				
Parkers Ridge[2]	silty-sand	1227	11.8	this study[3]
Rondane, Norway	silty-clay	1489	14.6	Williams (1959)
Okstindan, Norway	silty-sand	1583	15.5	C.Harris, (1977)
Taseriaq, Greenland	sandy-silt	1617	15.9	Everett, (1967)
Mesters Vig, Greenland	sandy-silt	1888	18.5	Washburn (1967)

1. derived in part from C.Harris (1981a:109).
2. not corrected for particles coarser than 2.00 mm.
3. see C.Smith (1979) for comparable measurements from the same general area.

5.5 Summary

This chapter has reviewed the results of a series of field and laboratory studies designed to describe the geomorphic character of the 58 turf-banked solifluction lobes selected for process monitoring. The aim of this research was to highlight possible spatial variances in these properties which might have an influence on solifluction dynamics within this region. The results of several of these investigations appear to be significant. The most noteworthy of these findings were:

1. An analysis of the morphological structure of the 58 study lobes revealed that all of them share similar forms. This suggested that solifluction processes at the different sites were similar in character, thus ensuring the comparability of the lobes sampled.
2. The morphology of the turf-banked solifluction lobes selected for study was controlled by the slope on which they occurred. Specifically, small high-fronted lobes were found to develop on steeper slopes, while large high-fronted lobes were discovered on low angle slopes. These observations substantiate the findings of Hall (1981) and Heilbroonn and Walton (1984a).
3. Analysis of three locational parameters offered some explanation for the differential spatial distribution of the sample lobes. Most of the lobes were found concentrated (86.2%) on moderately steep slopes (18.8° ± 6.8°) within a very narrow altitudinal zone (approximately 200 m in extent) located immediately above the local treeline. These observations support the notion that solifluction lobes occur mainly on slopes of between 15° to 25° because of the associated downslope shearing forces common to these gradients (c.f. Rapp, 1960; C.Harris, 1977). In addition, these results demonstrated that the main zone of solifluction in this mountainous setting corresponds closely to the periglacial ecotone defined by the upper limits of the alpine treeline (see Figure 3.2). Analysis of the locational data did not, however, point out any specific preference for solifluction lobes to be located on slopes of a particular orientation, that could not be explained by local surface conditions.

4. In general, the sediment of the 58 study lobes was discovered to be a highly frost susceptible silty to stony loam. No significant spatial variances were detected in this textural characteristic.
5. Virtually all of the sediments examined have relatively low liquid limits, which in inorganic soils tend to be associated with a lack of cohesion and a propensity for viscous displacements (C.Harris, 1981a:108).
6. In general, these solifluction sediments have very low plasticity indexes. This property indicates that they will be sensitive to even slight changes in their natural water content. As a result fundamental changes in the mode of displacement would be expected, from plastic to viscous flowage, with only minor soil water adjustments.
7. Wide areal variations in the unit weights of these solifluction sediments were indicated.

Clearly, the results of these analyses define a relatively representative sample from the population of solifluction lobes. The data indicates that the 58 lobes share both many morphological and many sedimentological properties. This observation is crucial in the context of the following chapter which discusses and compares the rates of contemporary solifluction movements which occurred at these lobes over the study period.

6. CONTEMPORARY SOLIFLUCTION ACTIVITY : RATES

6.1 Introduction

The geomorphic activity of present-day solifluction processes within the Alberta Rocky Mountains was poorly known prior to this study. Previous researchers had confirmed the activity of related slope processes such as soil creep (S.Harris, 1971,1973) and gelifluction (Luckman, 1973), however descriptions of the rate and character of solifluction were lacking entirely. Thus, the principal focus of the research discussed in this chapter was to document the nature of contemporary solifluction movements occurring within the three study areas. This was accomplished through a process monitoring program designed to document contemporary solifluction activity at each of the turf-banked solifluction study lobes. By conducting the study in this manner, it was possible, first of all, to establish the general character of solifluction within the Alberta Rocky Mountains field area. Secondly, it was then possible to examine the nature of both spatial and temporal variances in solifluction movements within the field area and within each of the study areas.

6.2 Measurements and Observations

This evaluation of solifluction movements was based upon process measurements completed at 45 of the 58 study lobes. Solifluction movements at the remaining study lobes were not evaluated, either because the measurement inserts used could not be relocated or had been disturbed by inquisitive ground squirrels (***Sermophilus columbianus citellus***).

For this study, three independent measurement techniques were employed to monitor solifluction movements: inclinometer tubes (41 lobes); dowel pillar columns (15 lobes); and painted stone networks (7 lobes). Each offered a different perspective on the solifluction mechanisms involved and, together, they provided a precise measure of the rate of annual movement. To control for measurement insensitivities peculiar to each of the techniques, replicate monitoring was completed at approximately 33 percent of the monitoring sites. This either involved the duplication of a particular procedure or the juxtaposition of a complementary procedure. Table 6.1 indicates the study lobes where each of the measurement techniques was successfully employed and provides an indication of where comparable data were derived.

All three measurement techniques were used to provide a linear measure of annual surface transport rates (cm/year). However, only the inclinometer tubes and the dowel pillars provided a record of net sediment transport. This annual volumetric movement was described per cm unit of contour, as cm^3/cm/year (cubic centimeters per centimeter width of slope per year) and was derived by measuring temporal changes recorded by the vertical velocity profiles.

Each inclinometer tube and dowel pillar site was positioned approximately 0.5 m behind the snout, where a concentration of flow is normally found (c.f. Washburn, 1967:88; Benedict, 1970:181). Movements recorded here were expected to reflect the contributions of both frost creep and gelifluction mechanisms. Where larger networks of columns and/or tubes were installed, such as at Lobe 50 in the Parkers Ridge area, the positioning of the inserts was dictated by local site characteristics. In addition, a limited number of inserts were positioned in front of several lobes for comparative purposes.

Positioning of the painted stone networks was designed to measure differential movement on the tread surfaces. Each network consisted of a number of monitoring positions spaced across the lobe apex. Similar networks, positioned in front of several lobes, provided an independent estimate of slope mobility on the parent slope (see **Figure 5.1**).

More precise details of the experimental procedures and their results are contained in the following sections.

6.2.1 Inclinometer Tubes

The first measurement technique involved the use of flexible inclinometer tubes. Proven useful in a wide array of mass wasting studies (Owens, 1969; Barr and Swanston, 1970; Bovis, 1974), this procedure has been used successfully in a number of previous investigations into

Table 6.1 : Study lobes at which the three measurement techniques yielded results.

area	lobe #	Inclinometer Tubes	Dowel Pillars	Painted Stones
MT.RAE AREA				
	1	•		
	3		•	
	4	•		
	10	•	•	•
	11	•		•
	12	•		
	13	•	•	•
	14	•	•	•
	21			•
	22	•		
	23		•	•
	24	•		
	25	•	•	
	26		•	
	28	•		
	29	•		
	34	•	•	
	35	•	•	
	41	•		•
	42	•		
	43	•		
	44	•		
	45	•		
MT.ALLAN AREA				
	5	•		
	6	•		
	7	•		
	9		•	
	30	•		
	31	•	•	
	32	•		
	33	•	•	
	36	•		
	37	•	•	
	38	•	•	
	46	•		
	47	•		
PARKERS RIDGE AREA				
	50	•		
	51	•		
	52	•		
	53	•		
	54	•		
	55	•		
	60	•		
	61	•		
	62	•		

solifluction (Williams, 1957, 1962a, 1966; Zhigarev, 1967; Price, 1970a, 1973; C.Harris, 1972, 1977; Mackay, 1981). It involves the insertion of plastic tubing into the ground which is then free to move with the soil. Subsequent observations of changes in the tube profiles provide a depth-integrated measure of soil displacement. Unfortunately, however, this technique does not permit internal shear zones to be identified (Price and Alexander, 1971; Anderson and Finlayson, 1975).

For this study a total of 60 inclinometer tubes were installed in 1980 and 1981 at 48 lobes throughout the study areas. Tube installation followed a standard procedure. Initially, a thin-walled tube auger (1.9 cm outside diameter) was hammered vertically into the ground to create an implantation hole with an overall depth close to 1 m. Thick-walled, hollow plastic tubing (1.9 cm outside diameter, 1.15-1.25 cm inside diameter), heat-sealed at its bottom end, was then eased into each hole using an implantation rod. The rod was then removed, the tubes trimmed flush with the ground surface and sealed with cork stoppers.

Soil movements recorded by the inclinometer tubes were measured with the aid of an inclinometer probe designed to fit into the interior of the tubes. Two probes (11.5 and 12.5 mm in diameter) were manufactured for this purpose by the Electronics Division, Technical Services, University of Alberta. While similar in design to the probes described by Williams (1962b), they incorporated the technological refinements utilized by Bovis (1974:192-198). Each probe consisted of a pair of high-elongation strain gauges (Deltronics Inc., 202YME strain gauges) mounted on either side of a narrow steel spring (15 cm in length) encapsulated within a DowCorning silicon rubber compound. Flexing of the probe corresponded to departures from zero on an attached D.C. Wheatstone bridge circuit modified to permit x10 and x100 signal amplification. Each of the probes was calibrated so that the meter readings described radii of curvature having upslope and downslope convexities. This was accomplished by matching the bridge readings against arcs of known radii on a specially constructed calibration board (c.f. Bovis, 1974:199-205).

Annual surveys of the tube profiles were completed annually between 1980 and 1983. Unlike the biweekly readings performed by Price (1970a), this annual interval ensured that disturbances resulting from measurement of the tubes was minimized (Bovis, 1980, personal communication). These surveys were undertaken in mid August, when drying and settlement had largely stabilized the soil. To prevent spurious data generation, the protruding lip of each buried tube was secured during the measurement procedure. Four sets of readings, two upslope and two downslope, were made at 2 cm intervals. To ease the movement of the probe within the tube, a lubricant (Yellow77-Wire Pulling Lubricant, IDI Electrict (Canada) Limited) was liberally applied. Results of these surveys were averaged at each 2 cm coordinate to provide a filtered raw value (Kalkani, 1980). Because it was assumed that the base of the tube remained stationary, the shape of the buried tube was reconstructed by incremental coordinate plotting of the angular deflection of the tube profile between each 2 cm point. This was accomplished using the methodology outlined by Bovis (1974), which provided more precise measurements than the procedure described by Williams (1962b). Annual soil movements were established by comparing yearly changes in the vertical velocity profile of each tube. Measurements made soon after the installation of tube provided a reference profile against which surface movements and volumetric displacements were calculated. Several measured tubes were excavated in 1981 and 1982 to substantiate the accuracy of this procedure. No significant variations were detected between the actual and the computed deformation profiles.

6.2.1.1 Observations

Annual probing of the inclinometer tubes demonstrated soil displacements of varying character and magnitude. Although several of the tubes implanted in 1980 and 1981 were lost to animal disturbance or deliberate excavation, in total 118 plot-years of tube data were collected by 1983 at 41 different solifluction lobes.

Solifluction displacements recorded by the inclinometer tubes are summarized in Table 6.2 (see Appendix I for complete records). Soil movements at the ground surface ranged up to a maximum of 2.25 cm/year. In the majority of cases soil movement decreased rapidly below

Table 6.2 : Solifluction movements recorded by inclinometer tubes.

Lobe #	Period	Tube Depth Below Surface cm	Maximum Depth of Mov't cm	Annual Surface Mov't cm/yr	Annual Volu -metric Mov't cm^3/cm /yr	Shape Down -slope
MT.RAE AREA						
1	1980-1983	95.0	44.0	0.25	9.80	convex
4	1980-1982	81.0	30.0	1.00	17.55	concave
10	1981-1983	88.0	51.0	0.58	20.57	concave
11	1980-1983	75.0	16.0	0.70	3.27	concave
12	1980-1983	86.0	24.0	0.73	7.16	concave
13	1980-1983	69.0	30.0	1.02	13.03	concave
14	1980-1983	87.0	25.0	0.80	9.90	concave
22	1980-1982	80.0	28.0	1.05	14.11	concave
24	1980-1982	100.0	40.0	0.00	10.38	convex
25	1980-1981	100.0	23.0	0.50	10.20	convex
26	1980-1982	95.0	35.0	0.63	19.51	convex
28	1981-1982	54.0	7.0	0.40	1.30	concave
29	1980-1982	83.0	25.0	1.35	17.19	concave
34	1980-1983	98.0	29.0	0.89	13.93	concave
35	1980-1983	97.0	37.0	0.93	20.26	convex
41	1981-1983	76.0	16.0	0.10	1.65	concave
42	1980-1983	74.0	26.0	0.90	10.48	concave
43	1980-1982	79.0	16.0	0.50	3.88	concave
44	1981-1983	84.0	16.0	0.60	4.85	concave
45	1980-1983	76.0	17.0	0.53	4.85	concave
MT.ALLAN AREA						
5	1981-1983	105.0	30.0	0.53	6.93	concave
6	1980-1983	96.0	27.0	0.73	14.03	concave
7	1980-1983	86.0	40.0	0.60	11.59	concave
30	1982-1983	89.0	29.0	2.10	29.20	concave
31	1980-1983	102.0	34.0	1.02	14.74	concave
32	1980-1983	90.0	39.0	0.93	21.54	concave
33	1980-1983	87.0	47.0	0.93	25.89	concave
36	1980-1983	112.0	27.0	1.20	14.38	concave
37_1	1980-1983	97.0	65.0	2.25	59.61	concave
37_2	1980-1983	112.0	18.0	0.53	3.57	concave
37_3	1980-1983	60.0	19.0	0.62	4.57	concave
38	1980-1983	112.0	51.0	1.70	18.30	concave
46	1980-1981	101.0	24.0	1.50	17.25	concave
47	1980-1981	98.0	34.0	0.10	7.95	concave
PARKERS RIDGE AREA						
50_2	1981-1983	109.0	62.0	0.55	24.08	concave
50_3	1981-1983	99.0	56.0	0.88	9.82	concave
50_4	1981-1983	107.0	35.0	0.80	13.41	concave
50_5	1981-1983	108.0	56.0	1.20	23.59	concave
51	1981-1983	104.0	55.0	1.30	18.36	concave
52	1981-1983	107.0	13.0	0.90	7.73	concave
53	1981-1983	100.0	22.0	1.00	18.66	concave
54	1981-1983	107.0	37.0	0.15	3.65	concave
55	1981-1983	112.0	44.0	0.80	16.02	concave
60	1981-1983	92.0	59.0	1.50	24.76	convex
61	1981-1983	100.0	0.00	0.00	0.00	
62_1	1981-1983	92.0	19.0	0.70	5.73	concave
62_2	1981-1982	65.0	60.0	0.50	19.33	convex

the ground surface, being confined to the upper 0.35 m of sediment (Table 6.2). The deepest movements detected occurred at Parkers Ridge, where downslope motion was observed 0.55 m below the surface at several lobes. The volume of sediment moved annually varied considerably, ranging from less than 2 to to greater than 50 cm^3/cm/year.

Figure 6.1 illustrates three typical velocity profiles obtained with the inclinometer tubes. The majority of the tube profiles (85 percent) appear like those at Lobe 10 in the Mt.Rae area and Lobe 37 in the Mt.Allan area. This concave downslope profile describes a uniform decrease in displacement with depth which has often been found in association with solifluction movements (Rudberg, 1958, 1962; Williams, 1966; Price, 1970a). Only a small number of convex profiles (15 percent), like that at Lobe 26 in the Mt.Rae area, were measured. Suggestive of subsurface shearing, similar differential soil movements within solifluction soils have been discussed by Benedict (1970), C.Harris (1973) and Price (1973).

6.2.2 Dowelling Pillars

The second technique chosen to measure solifluction movements utilized vertical columns of dowelling pillars. First employed by Rudberg (1958, 1962), this technique has subsequently been used in a number of solifluction studies (Benedict, 1970; C.Harris, 1973; Jahn and Cielinska, 1974; Gamper, 1981). It involves the insertion of vertical columns of wooden dowel pegs into the soil. Observation of changes from the assumed initially vertical profile, provide a measure of downslope displacement (Rudberg, 1967). Unlike the inclinometer tubes, this is a long-term technique because precise measurement is difficult and excavation disturbance renders further measurements dubious (Anderson and Cox, 1978:86). The advantage of this technique is its inherent capacity to illustrate shear planes within the moving soil.

For this study 22 dowel pillar columns were implanted in 1980 in the Mt.Rae (n=13) and Mt. Allan (n=9) areas. These columns consisted of 2.5 cm segments of 1.3 cm wide dowelling stacked in vertical boreholes of the same diameter. On average these columns

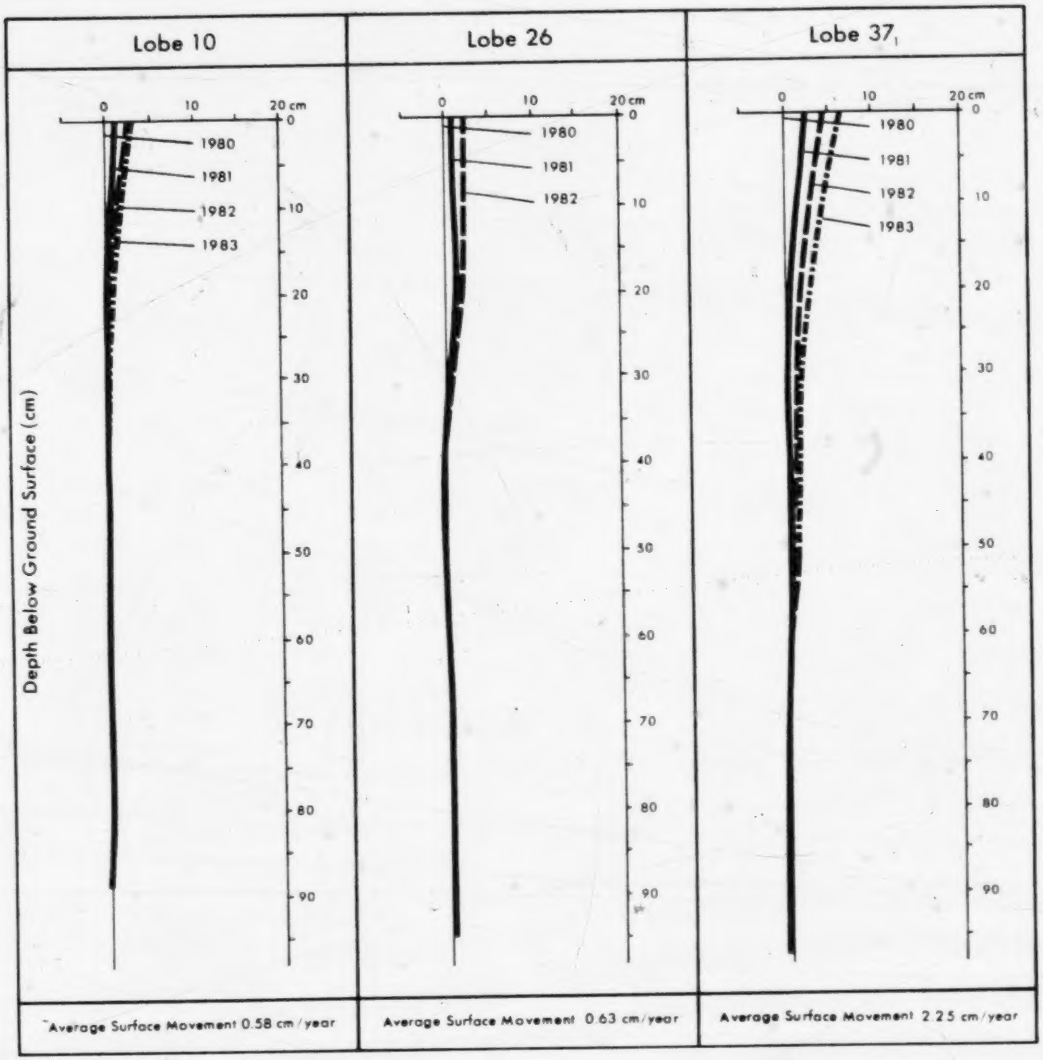


Figure 6.1 : Three examples of solifluction movements recorded by inclinometer tubes.

extended from 0.50 to 1.25 m below the ground surface. Two additional columns located in the Mt. Rae area were a legacy of earlier investigations (D.Smith, 1979:227). Installed in 1977, in Lobe 3 and 10 in the Mt.Rae area, they consisted of 5 cm lengths of 1.3 cm wide dowelling. Excavation of two pilot columns in 1980 soon after their installation revealed no significant problems with the implantation procedure.

Movements recorded by the peg columns were observed in pits dug adjacent to the implantation sites. These excavations extended below the deepest peg and left the columns exposed along a vertical face. A vertical plumb-line was then dropped from the soil surface to the deepest peg, which was assumed not to have moved. The horizontal distance from this line to the top and bottom of each displaced dowel plug was then measured to the nearest 0.1 cm. Annual movement rates were averaged by dividing these horizontal displacements by the elapsed time since installation.

6.2.2.1 Observations

Excavations in 1981 and 1982 revealed the effects of 26 plot-years at 15 different dowel pillar sites. Movements at each column are listed in Table 6.3 (see Appendix II for complete record). Unfortunately, the positions of another 9 of the columns could not be re-established.

The dowel pillars revealed a wide range of mass movement, with surface displacement rates varying up to more than 1 cm/year. At several sites (eg. Lobes 9, 26, 29) movement was not detected over the two year period (1980-1982). In marked contrast was the situation at Lobe 37 in the Mt.Allan area, where surface movement averaged 2.5 cm/year between 1980 and 1982. Volumetric rates also varied greatly, ranging up to greater than 50 cm^3/cm/year (Table 6.3).

Like the displacements shown by the inclinometer tubes, downslope movements detected by the dowelling pillars were relatively shallow. On average, little activity occurred below 0.30 m. However, measurements made over longer time frames (Lobe 3 and 10) suggest that this observation is temporally biased, since there appears to be a tendency to record deeper movements over time. Generally though, on an annual basis, between 0 and 50 cm^3/cm/year

Table 6.3 : Solifluction movements recorded by dowel pillars.

Lobe #	Measurement Period	Column Depth Below Surface cm	Maximum Depth of Mov't cm	Annual Surface Mov't cm/yr	Annual Volu-metric Mov't cm^3/cm /yr	Shape Down-slope
MT.RAE AREA						
3	1977-1981	70.0	43.0	0.50	12.26	concave
10	1977-1982	52.0	41.0	0.74	17.09	convex
13	1980-1982	40.0	28.0	1.13	13.17	concave
14	1980-1982	52.5	28.0	1.00	19.64	convex
23	1980-1982	50.0	27.0	0.70	11.40	concave
25	1980-1982	52.5	14.0	0.60	2.50	concave
26	1980-1982	75.0	0.00	0.00	0.00	
29	1980-1982	52.5	0.00	0.00	0.00	
34	1980-1982	60.0	29.0	nd[1]	nd	convex
35	1980-1982	50.0	24.0	0.75	18.34	concave
MT.ALLAN AREA						
9	1980-1982	73.0	0.00	0.00	0.00	
31	1980-1982	73.0	27.0	0.50	nd	convex
33	1980-1982	75.5	28.0	0.75	11.48	concave
37	1980-1982	57.5	38.0	2.50	51.70	convex
38	1980-1982	72.5	28.0	0.75	25.43	convex

1. nd = no data

was transported at the pillar sites between 1980 and 1982.

An examination of the velocity profiles shown in Figure 6.2 demonstrates that downslope movement occurred in a variety of ways. As is illustrated at Lobe 3 in the Mt.Rae area, soil displacements at many of the columns (50 percent) resulted in concave downslope profiles. These profiles describe a uniform decrease in displacement with depth. Most of the remaining profiles appear like the plug-like convex downslope profiles found at Lobe 10 in the Mt.Rae area and Lobe 37 in the Mt.Allan area. At Lobe 37, where the surface layers of soil apparently lagged behind deeper seated movements, the vegetation likely obstructed surface movements (Jahn and Cielinska, 1974:97). In only a few instances, did the dowel pillar

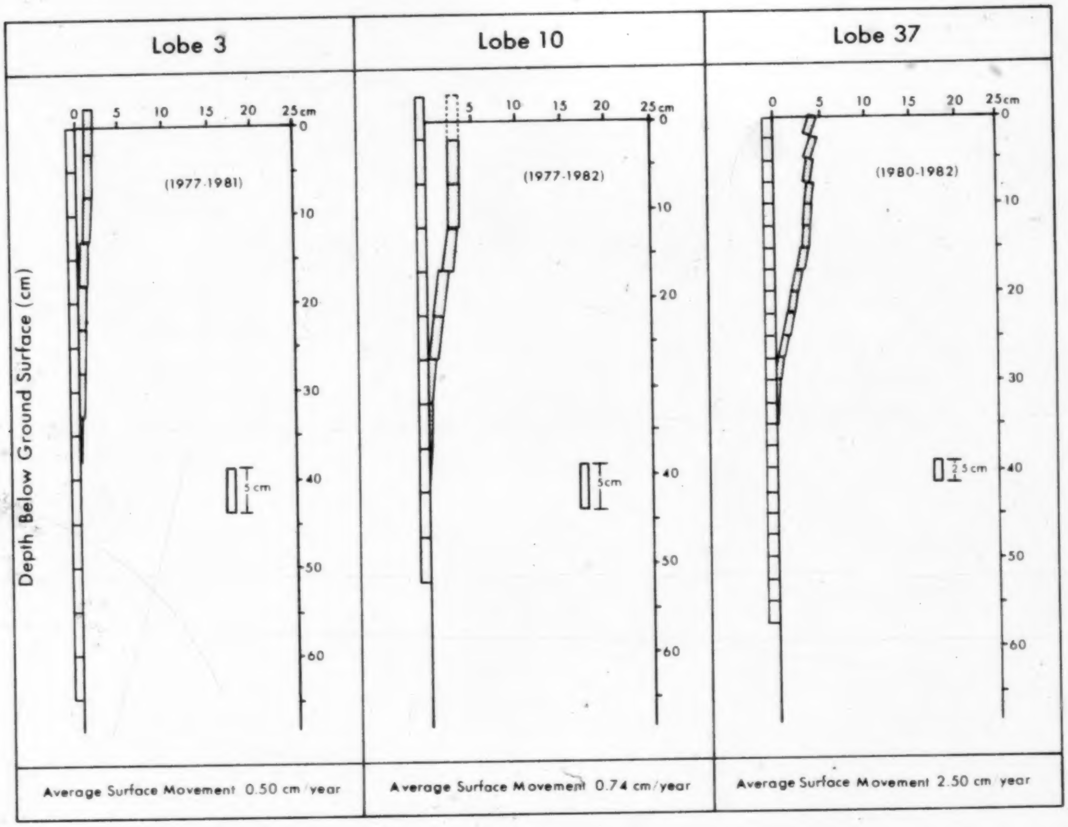


Figure 6.2 : Three examples of solifluction movements recorded by dowel pillars.

profiles illustrate marked zones of shearing. An exceptional example was discovered at Lobe 38 in the Mt.Allan area, where movement was entirely restricted to the upper 28 cm of soil.

6.2.3 Painted Stones

The third technique used to detail solifluction activity involved repeated surveys of established distances between painted networks of stones and benchmarks. While utilized in a large number of previous solifluction studies (Michaud, 1950; Rudberg, 1958, 1962; Rapp, 1960; Barnett, 1966; Demek, 1967; Price, 1970a, 1973; Rapp and Stromquist, 1979; Soderman, 1980), estimates of solifluction rates derived from this procedure are often imprecise (c.f. Price and Alexander, 1971:136; Anderson and Finlayson, 1975:34). Some of the inherent methodological ambiguities can be controlled by only monitoring movements found associated with *in situ* stones (Kirkby and Kirkby, 1974; Caine, 1981). However, even the movement of embedded stones involves uncertainties because of their varying penetration depths (Rapp, 1967; Price and Alexander, 1971; Hollerman, 1979). Despite these problems, the simplicity and low cost of this technique favours its use where wider replication is desired.

Painted stone networks were used to monitor solifluction at two study sites in the Mt.Rae area. At K2, 122 *in situ* stones at 6 different solifluction lobes (Lobes 10, 11, 13, 14, 21, 41) were marked with a small painted *x* for measurement purposes in 1980. In the same year 13 stones at a single site in Tombstone Valley (Lobe 23) were similarly marked. These marks were subsequently tied together in a survey network using a steel tape. Immobile base-rocks or deep-seated survey posts served as benchmarks. The painted stone network established at Lobe 21 in July of 1980 is shown as an example (Figures 6.3 and 6.4). Annual surveys of distance changes from the benchmarks were used to estimate rates of movement. Throughout the measurement program the same steel tape was used under similar temperature conditions to measure distances to the nearest 0.1 cm.

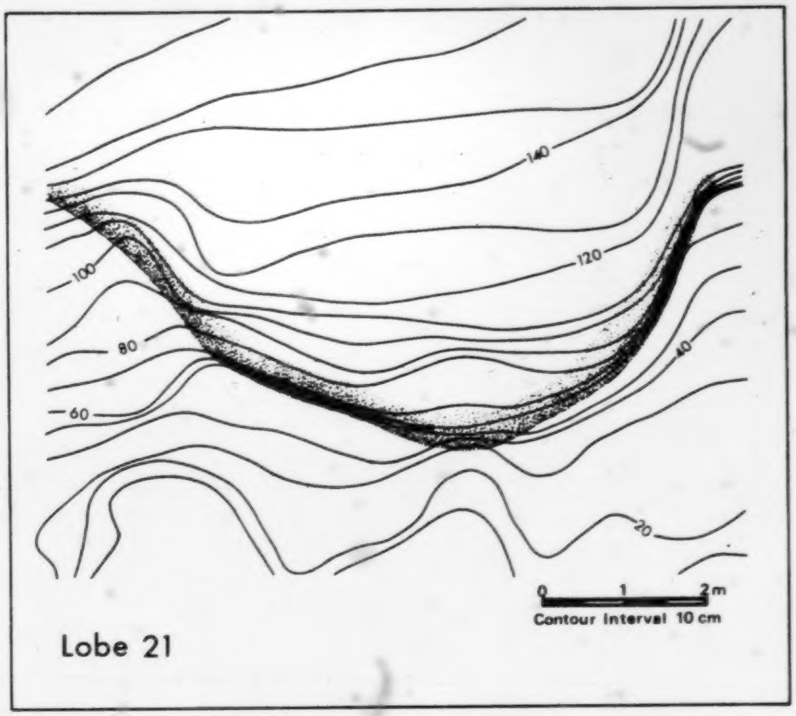

140
120
100
80
60
40
20
0
1
2m
Contour Interval 10 cm
Lobe 21

Figure 6.3 : Microtopography at Lobe 21, K2 study site, Mt.Rae area.

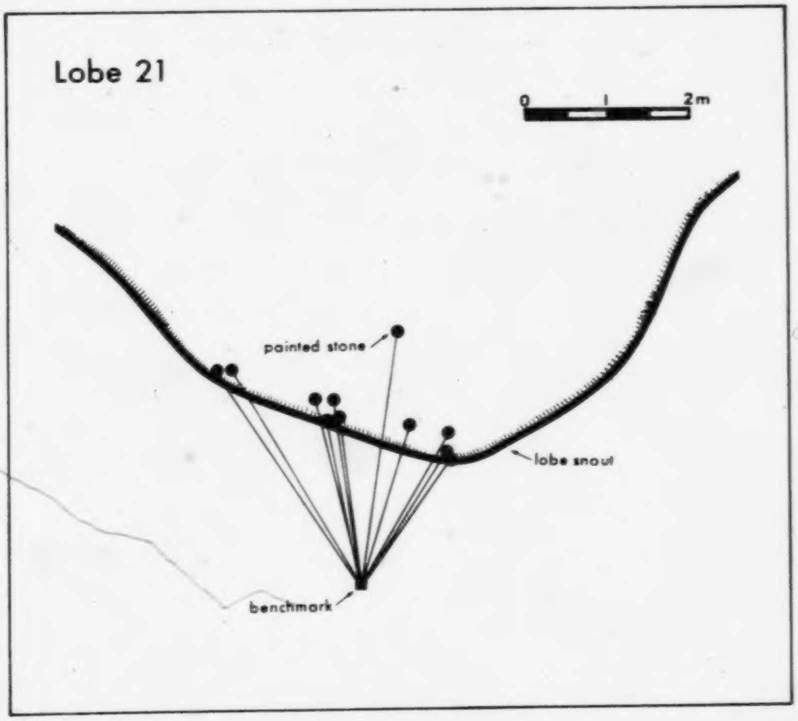

Lobe 21
0
1
2m
painted stone
lobe snout
benchmark

Figure 6.4 : Painted stone network installed at Lobe 21 in July 1980.

6.2.3.1 Observations

Annual surveys of the painted stones were completed in 1981, 1982, and 1983. While several of the marked stones were lost over the measurement period, the data total 305 plot-years of record. Annual summaries of these records are presented in Table 6.4 (see Appendix III for complete record).

Soil movements demonstrated by the painted stone networks illustrated a wide range of activity, varying from 0 to 1.17 cm/year. In all cases, the points showed marked year to year variability. Close examination of the painted stone data revealed that the rates of movement varied from the tread to the riser to the parent slope. In fact, a comparison of these measurements suggests the tread surfaces moved almost twice as fast as the adjacent parent slope, and nearly three times as fast as the adjoining riser (Table 6.5).

6.2.4 Comparison of the Measurement Techniques

Each of the three techniques chosen to monitor solifluction almost certainly incorporated some measurement error. In the case of the inclinometer tubes, despite the methodological improvements introduced in this study, instrumental impediments probably continued to influence measurement precision (Bovis, 1974; Kalkani, 1980). It was also clear that despite the care taken to measure displacements at the dowel pillar sites, some degree of imprecision remains inherent with the procedure (Anderson and Finlayson, 1975:21; Anderson and Cox, 1978:85). In addition, Caine's (1981) investigations of surface soil movement estimates derived from marked particles, established that a measurement bias is a virtually uncontrollable artifact of the technique itself.

Evaluation of the character of these errors is cognizant upon the assumption that each of the three types of measurement inserts was transported to a commensurate degree by the moving soil. While this is clearly not always the case (c.f. Owens, 1969; Anderson and Cox, 1978), in this study there do appear to be significant linear correlations between measurements revealed by the three techniques at individual lobes (Table 6.6). In the context of surface

Table 6.4 : Summary of surface movements at painted stone networks (1980-1983).

		ANNUAL MOVEMENT (cm/year)		
Lobe #	# points	1980 1981	1981 1982	1982 1983
10	18	0.50	0.50	0.28
11	24	0.38	0.38	0.09
13	36	0.80	0.80	0.52
14	6	1.08	1.08	1.30
21	11	0.36	0.25	0.09
23	13	0.65	0.50	
41	27	0.54	0.54	

Table 6.5 : Differential surface movements indicated by the painted stone networks (cm/year).

Lobe #	period	# points	parent slope	riser	tread
10	1980-1983	16	0.38	0.15	0.82
11	1980-1983	21	nd[1]	0.20	0.47
13	1980-1983	36	nd	0.41	0.58
14	1980-1983	5	nd	0.13	0.28
21	1980-1983	10	nd	0.19	0.51
23	1980-1982	12	nd	0.00	0.52
41	1980-1983	23	0.15	0.38	0.53

[1] nd = no data

Table 6.6 : Correlation matrix of instrument results.

	tubes	pillars	stones
SURFACE MOVEMENT			
Inclinometer Tubes	1.000	0.778[1]	0.603[2]
Dowel Pillars		1.000	0.890[1]
Painted Stones			1.000
VOLUMETRIC MOVEMENTS			
Inclinometer Tubes	1.000	0.825[1]	
Dowel Pillars		1.000	

1. significance = 98%.
2. significance = 90%.

movements the best correlation (r=0.890) was found between the dowel pegs and the painted stones, where 79 percent of the variation occurred around the mean. The poorest correlation (r=0.603) appeared between the inclinometer tubes and the painted stones, where only 36 percent of the variation could be explained. A similar evaluation of the volumetric movements indicated a significant correlation (r=0.825) between measurements derived from the inclinometer tubes and the dowel pegs. These relatively uniform responses to soil movements suggest that all three measurement techniques performed about equally and had a similar sensitivity to solifluction. Hence, these measurement values were assumed to be complementary and sufficiently similar to suggest they be pooled in the following discussions.

6.2.5 Discussion

The solifluction activity described by these measurements showed that the majority of movement occurred near the soil surface. Both the inclinometer tubes and the dowel pillars indicated that solifluction was largely concentrated within sediments above the 50 cm mark (Tables 6.2 and 6.3).

Surface movements at the study lobes ranged up to 2.5 cm/year. The slowest rates of movement occurred in the Mt.Rae area, where the average surface transport recorded by the three techniques was 0.66 cm/year (range 0.00 to 1.35 cm/year). In the Parkers Ridge area surface movements occurred at a slightly greater rate, averaging 0.79 cm/year (range 0.00 to 1.60 cm/year). The highest rates of activity were recorded in the Mt.Allan area, where surface transport averaged 1.04 cm/year (range 0.00 to 2.50 cm/year). These surveys indicated that the average rate of solifluction within the Alberta Rocky Mountains field area was approximately 0.83 cm/year.

Volumetric transport rates demonstrated similar activity patterns. Like the surface movements, the lowest rates were recorded in the Mt.Rae area where they averaged only 11.40 cm^3/cm/year (range 0.00 to 20.57 cm^3/cm/year). The highest average rates of volumetric transport were recorded at Parkers Ridge (mean 16.02, range 0.00 to 24.76 cm^3/cm/year); although the maximum rate of volumetric movement occurred at Lobe 37 in the Mt.Allan area, where approximately 59.61 cm^3/cm/year of sediment was transported. In contrast, the average rate of activity in the Mt.Allan area was only 14.38 cm^3/cm/year (range 0.00 to 59.61 cm^3/cm/year). Collectively these data indicated that the annual volume of sediment transported by solifluction within the field area averaged 13.29 cm^3/cm/year.

A correlation analysis of paired sets of surface and volumetric movement data showed that there was a significant linear relationship between these two activity descriptors (Table

6.7). This is portrayed in Figure 6.5, where it is shown that each 0.5 cm of surface movement described approximately 9.4 cm^3/cm of soil transport. It should be noted, however, that this relationship was relatively weak in the Mt.Rae area where only 28 percent (r^2) of the variance could be explained. This does not necessarily conflict with the significant associations noted between these two movement parameters, but it does suggest that the character of solifluction transport might have differed among the three areas.

These observations of present-day solifluction rates within the Alberta Rockies are comparable to those observed in a variety of arctic and alpine locations (Table 6.8) . The contrast with rates recorded by Benedict (1970) and Price (1973) elsewhere in the North American cordillera, suggests there are broad spatial differences in the pattern of solifluction within this geographical area.

6.3 Solifluction Movements : Spatial and Temporal Patterns

These observations of solifluction indicated that there was considerable variation in the rate of solifluction within the Rocky Mountains field area over the study period. For instance, surface movements varied from zero to greater than 2.5 cm/year. Figure 6.6 demonstrates the variations in the yearly rates of solifluction recorded for different observation years within each of the study areas. The fact that there was such a large range in activity suggested that the mechanisms producing solifluction movement may have varied spatially and/or temporally. On the other hand, because this variation appears to be associated with only a few relatively high movements (over 1 cm/year), these spatial and/or temporal variations may have little statistical significance.

In order to evaluate the significance of the spatial and temporal trends in solifluction, the surface movement data and the volumetric transport rate data were analytically examined. This analysis was completed at two scales of investigation following the suggestions made by Caine (1979). Because the main focus of this investigation was to establish the general character of solifluction within the Alberta Rockies, the first part of this analysis assessed the

Table 6.7 : Correlation between surface and volumetric movements.

area	r	significance	r^2
Mt.Rae	0.526	98%	0.28
Mt.Allan	0.875	99%	0.77
Parkers R.	0.863	99%	0.74
FIELD AREA	0.790	99%	0.62

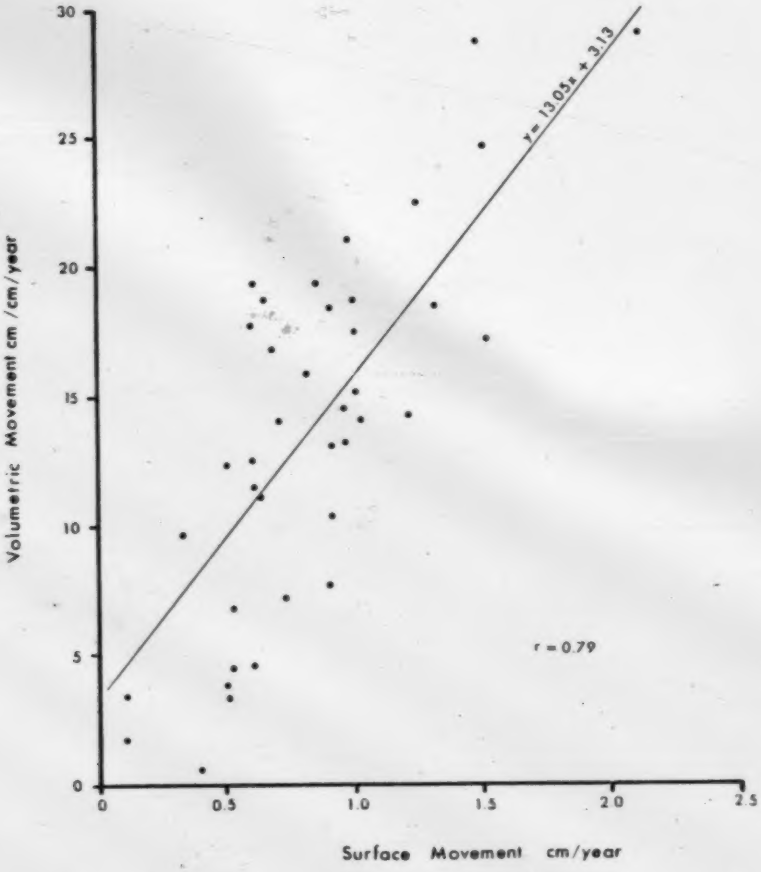


Figure 6.5 : Linear correlation between surface movement and volumetric movement rates.

Table 6.8 : Average rates of solifluction movement measured by inclinometer tubes and velocity columns.

source	location	number of profiles	mean surface mov't (cm/yr)	volumetric transport ($cm^3/cm/yr$)	
				mean	max.
this study	Mt.Rae	27	0.66	11.4	29.8
	Mt.Allan	18	1.04	18.8	57.7
	Parkers R.	13	0.79	14.2	36.2
	FIELD AREA	58	0.83	14.3	57.7
Benedict (1970)	Colorado	1	2.40	59.0	59.0
Gamper (1981)	Switzerland	6	3.70	28.3	450.0
C.Harris (1981a)	Norway	3	1.60	26.0	33.0
Mackay (1981)	N.W.T.	7	0.53	33.0	52.0
Price (1973)	Yukon	10	3.50 -71.00	32.0	nd[1]
Rapp (1960)	Lappland	--	4.00	50.0	80.0
Rudberg (1964)	Sweden	7	5.00	39.0	100.6
Stocker (1984)	Carinthia	66	0.96 -4.95	nd[1]	nd
Williams (1966)	Quebec	4	9.80	114.0	134.0

1. nd = no data.

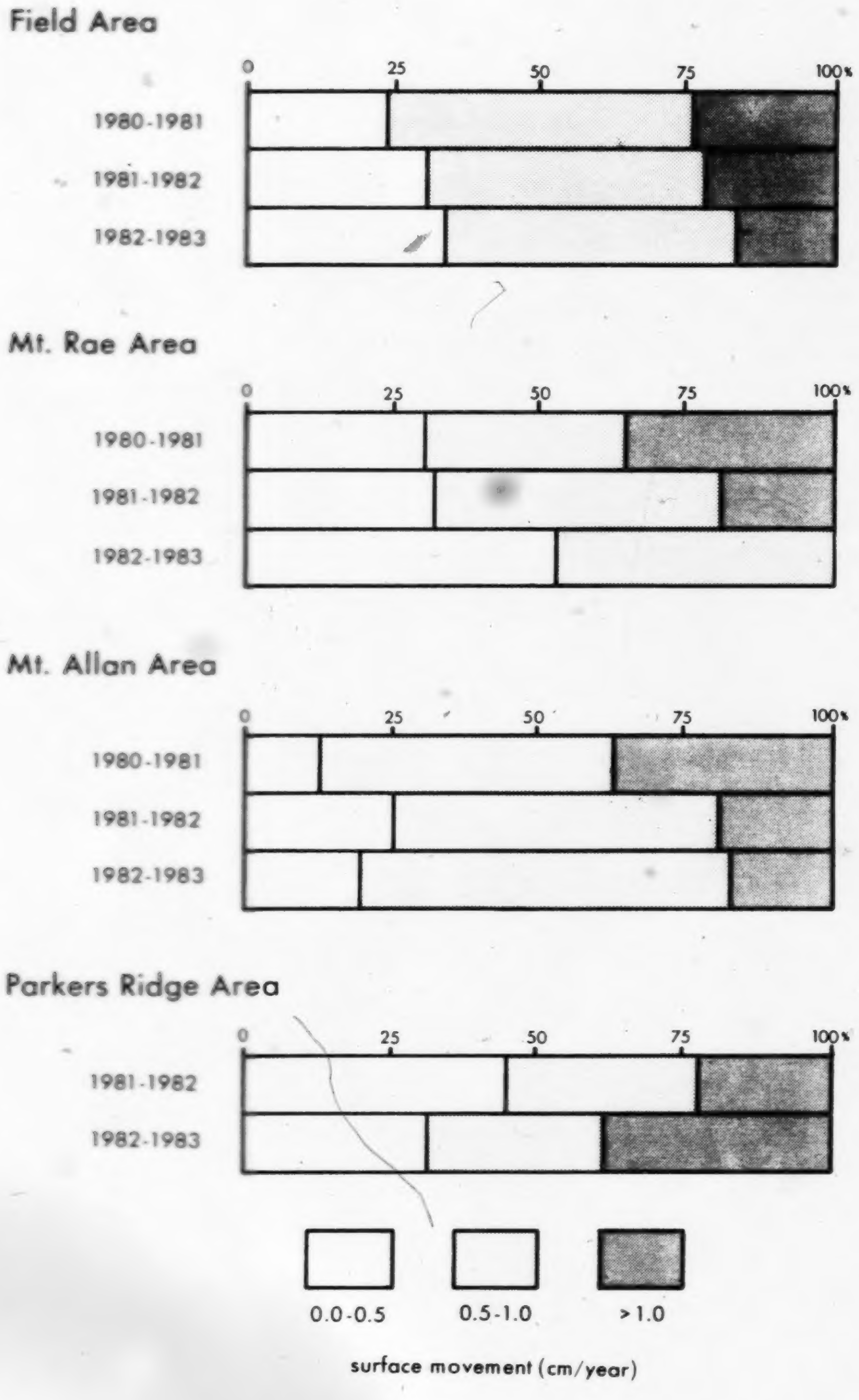


Figure 6.6 : Histograms illustrating the relative spatial and temporal distributions of surface movement rates.

nature of these space and time variations within and between the three study areas. The second part of this analysis attempted to highlight the characteristics of solifluction rate variations at each of the major study sites.

6.3.1 Analytical Framework

Two analytical approaches were utilized in this investigation of the variability of solifluction within the field area. Following Caine (1968), the log-normal model was used to evaluate the spatial and temporal variances in solifluction within and between the three study areas. As well, the coefficient of variability was used to establish the characteristics of solifluction at each of the study sites because of the relatively small sample sizes represented at this scale of investigation.

The log-normal model assumes that soil movements tend to be homogeneous at equivalent scales (Caine, 1979:17) because of the low probability of uphill displacement (Owens, 1969:217; Bovis, 1982:5). Its application, in the context of spatial and temporal variations within each of the study areas, seems appropriate especially given the demonstration of downslope solifluction within these areas. The effect of logarithmic transformation is to normalize the data, making the sample variances independent of the mean (Caine, 1982:54). Hence, the geometric mean emerges as the best measure of average movement and the standard deviation range as an indication of dispersion around the mean. To allow for the use of zero values in this analysis, 0.1 cm was added to all of the observations and later subtracted from the geometric mean (Caine, 1968:3).

The dimensional character of solifluction at the different study sites was evaluated using the coefficient of variability (CV). Providing a measure of the local activity patterns, it is defined as CV = $(s/x) \times 100$; where s is the standard deviation of the sample and x is the sample mean (Luk, 1982:248). Coefficients greater than 50 percent indicate a consistent tendency to right skewness (Bovis, 1982:5), whereas values greater than 100 percent indicate a standard deviation in excess of mean movements (Gardner, 1982:175).

6.3.2 Observational Data

These data were derived from the procedures discussed in the preceeding section. Two groups of measurements, surface movement rates (cm/year) and volumetric transport rates (cm^3/cm/year), were extracted for analysis.

The first group of measurements describe surface movements recorded by the inclinometer tubes, the dowel pillars and the painted stone networks. In total, it contained 447 observational plot-years of data surveyed at 185 individual data points. For this analysis, however, measurements derived from the painted stone networks were averaged to provide single point values at each of the seven monitored lobes. While this was done mainly to increase the comparability of the three measurement sets, it effectively reduced the data base to 149 plot-years of observation at 48 points.

The second group of measurements, describing volumetric transport rates, was derived from the inclinometer tube readings and the dowel pillar measurements. It contained a total of 126 plot-years of observation measured at 44 different points.

6.3.3 Results of Analysis

The existence of spatial and temporal variations in the rate of solifluction movement within the field area was illustrated in Figure 6.6. The nature of this variability is reviewed within the context of the different study areas and major study sites in order to better characterize the dynamics of solifluction within the Alberta Rockies.

6.3.3.1 Study Area Variability

Previous research has demonstrated that soil movement data is log-normally distributed, providing a representative sample of displacements is collected (c.f. Bovis, 1978; Bovis and Thorn, 1981; Caine, 1982). There seems to be little doubt that the amalgamated sets of surface and volumetric movement data collected within the field area do in total define a normal distribution and are, thus, representative of solifluction activity within this region. This point was emphasized by successful chi-square tests of their log-normality (Table 6.9).

Table 6.9 : Chi-square goodness of fit test to log normality for field area.

	computed chi^2	tabulated chi^2 (p=.10)	df	cases
Surface movements	12.40	13.30	4	62
Volumetric movements	3.11	10.60	6	58

Unfortunately, the normality of the movement data collected within each of the study areas could not be conclusively established by chi-square testing because of the relatively small number of rate measurements collected within each area. However, as is shown in Figures 6.7 and 6.8, after log transformation both sets of movement data did approximate log-normal distribution curves within the three study areas. Thus, it was assumed that both were representative of solifluction movements at this scale of investigation.

The effects of using these logarithmic transformations are summarized in Tables 6.10 and 6.11. Both sets of movement data indicate there were only slight differences in the rate of solifluction among the three study areas. For example, mean surface movement had a limited range from 0.53 ± 0.19 cm/year in the Mt.Rae area; to 0.64 ± 0.21 cm/year in the Parkers Ridge area; to 0.78 ± 0.23 cm/year in the Mt.Allan area (Table 6.10). In fact, analysis of variance testing indicates that these spatial differences are insignificant when compared to variations in the mean rate of solifluction recorded within the entire field area (Table 6.12).

A comparison of volumetric transport rates showed that they, too, exhibited limited variation within the field area (Table 6.11). The highest rates of volumetric transfer occurred in the Mt.Allan area, where a mean value of 10.63 ± 4.04 cm^3/cm/year was indicated after logarithmic transformation. Volumetric movements within the other two areas were shown to range from 7.60 ± 3.11 cm^3/cm/year in the Mt.Rae area to a low mean rate of 7.20 ± 5.54 cm^3/cm/year in the Parkers Ridge area. Similar to surface movements, these spatial variations

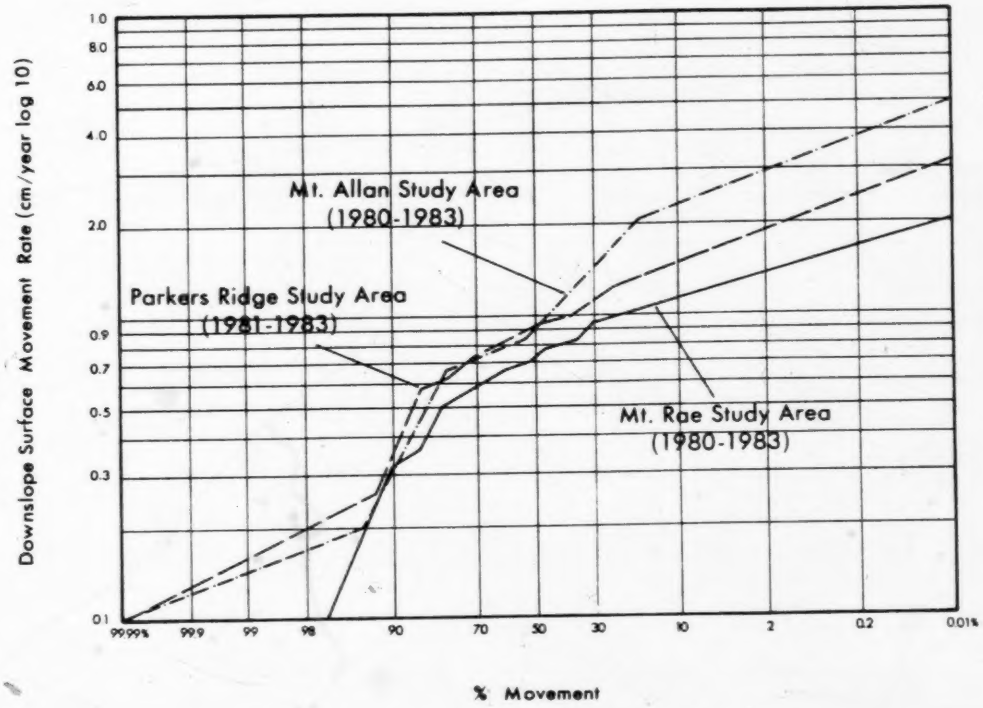


Figure 6.7 : Log-probability curves of surface movement data.

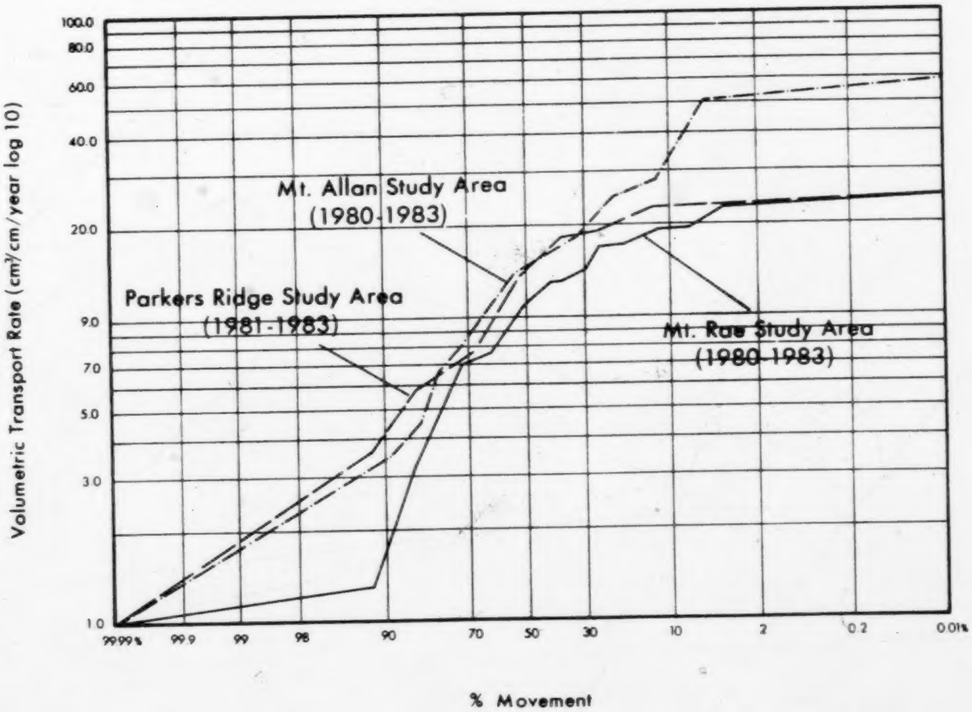


Figure 6.8 : Log-probability curves of volumetric movement data.

Table 6.10 : Surface movement data.

	Mt.Rae	Mt.Allan	Parkers Ridge	FIELD AREA
	1980 1983	1980 1983	1981 1983	1980 1983
# observations (plot years)	78	45	26	149
arithmetic mean (cm/year)	0.66	1.04	0.79	0.83
median (cm/year)	0.67	0.84	0.90	0.72
range (cm/year)	0.00 -1.35	0.00 -2.50	0.00 -1.60	0.00 -2.50
geometric mean ($\log_{10}$/year)	0.80	0.94	0.87	0.85
geometric mean (cm/year)	0.53	0.78	0.64	0.61
geometric s^2 ($\log_{10}$ cm/year)	0.08	0.12	0.10	0.10
geometric range (cm/year)	0.34 -0.73	0.55 -1.01	0.42 -0.85	0.40 -0.82

Table 6.11 : Volumetric movement data.

	Mt.Rae	Mt.Allan	Parkers Ridge	FIELD AREA
	1980 1983	1980 1983	1981 1983	1980 1983
# observations (plot-years)	58	42	26	126
arithmetic mean (cm^3/cm/year)	11.39	18.79	14.24	14.29
median (cm^3/cm/year)	11.40	14.38	16.02	13.29
range (cm^3/cm/year)	0.00 -20.57	0.00 -59.61	0.00 -24.76	0.00 -59.61
geometric mean (log_{10}/year)	1.89	2.03	1.94	1.94
geometric mean (cm^3/cm/year)	7.60	10.63	7.20	8.67
geometric s^2 (log_{10}/year)	0.23	0.35	0.49	0.31
geometric range (cm^3/cm/year)	4.49 -10.70	6.59 -14.68	1.66 -12.73	5.10 -12.24

Table 6.12 : One-way analysis of variance of surface movements (1980-1983).

source	SS	df	MS	F	signif.
Between -area	0.157	2	0.078	0.702	NS[1]
Within -area	4.667	42	0.111		
Total	4.824	44			

1. NS = not significant.

Table 6.13 : One-way analysis of variance of volumetric movements (1980-1983).

source	SS	df	MS	F	signif.
Between -site	0.038	2	0.019	0.062	NS[1]
Within -site	12.546	41	0.0306		
Total	12.584	43			

1. NS = not significant.

in volumetric transfer rates proved to be statistically insignificant when compared by one-way analysis of tests (Table 6.13).

Similarly, there did not appear to be any significant variations in solifluction activity within this region over the study period. Mean surface movement rates for each study area per measurement period are presented in Table 6.14. Although there were obvious changes in the mean values from year to year, analysis of variance testing indicated that these differences were statistically insignificant (Table 6.15). In the same manner, volumetric transport rates (Table 6.16) demonstrate insignificant fluctuations when compared on an annual basis (Table 6.17). From these relationships, it seems reasonable to conclude that, over the short-term of this study, the temporal pace of solifluction was similar throughout the field area. In addition, there do not appear to be any consistencies in movement trends through time among the three areas. While solifluction rates in the Mt.Rae area gave the appearance of decreasing over the study period, movements within the other two areas demonstrated inconsistent temporal shifts.

6.3.3.2 Study Site Variability

The wide range in solifluction rates within each of the study areas (Tables 6.10 and 6.11) implied that there may have been localized variations in the activity of solifluction within this region. This suggestion was not surprising given the range of environmental settings which characterize the study sites. The nature of these smaller scale variations were examined in this section in order to isolate any local variations in solifluction.

Solifluction activity was surveyed at a number of different study lobes located within each of the major study sites. These replicate data permitted an evaluation of the spatial and temporal characteristics of within-site movements using variability coefficients computed from the local means and standard deviations (c.f. Bovis, 1982; Gardner, 1982). The results of this analysis demonstrated several things. First of all, the average rate of solifluction, measured at each of the study sites did differ slightly over the study period (Tables 6.18 and 6.19). For instance, surface transport rates in the Mt.Rae area ranged from a low of 0.52 cm/year at the Tombstone Valley site to as high as 0.75 cm/year at the Ptarmigan Ridge site (Table 6.18).

Table 6.14 : Annual surface movement rates (cm/year), 1980-1983.

	1980-1981		1981-1982		1982-1983	
	mean[1]	(s^2)[2]	mean	(s^2)	mean	(s^2)
Mt.Rae	0.63	0.078	0.52	0.104	0.42	0.091
Mt.Allan	0.83	0.145	0.67	0.131	0.77	0.091
Parkers Ridge			0.43	0.131	0.61	0.186
FIELD AREA	0.69	0.104	0.54	0.118	0.56	0.910

1. geometric mean rate of movement for the period (cm/year).
2. sample variance ($\log_{10}$ units).

Table 6.15 : One-way analysis of variance of surface movements.

	df	F-value[1]	Signif.
Mt.Rae	2, 75	1.270	NS
Mt.Allan	2, 42	0.217	NS
Parkers Ridge	1, 24	0.747	NS
FIELD AREA	1, 111	3.415	NS

1. F-value = variance between-samples/variance within-samples.

Table 6.16 : Annual volumetric movements (cm^3/cm/year), 1980-1983.

	1980-1981		1981-1982		1982-1983	
	mean[1]	(s^2)[2]	mean	(s^2)	mean	(s^2)
Mt.Rae	9.66	0.240	6.95	0.330	6.45	0.108
Mt.Allan	11.53	0.469	10.11	0.446	7.62	0.474
Parkers Ridge			8.27	0.433	8.93	0.444
FIELD AREA	10.20	0.313	8.09	0.378	7.71	0.344

1. geometric mean rate of movement for the record period (cm^3/cm/year).
2. sample variance ($\log_{10}$ units).

Table 6.17 : One-way analysis of variance of volumetric movement.

	df	F-values[1]	signif.
Mt.Rae	2, 55	0.850	NS
Mt.Allan	2, 40	0.236	NS
Parkers Ridge	1, 24	0.017	NS
FIELD AREA	1, 86	0.342	NS

1. F-value = variance between-samples/variance within-samples.

Table 6.18 : Coefficient of variation of surface movement rates (cm/year).

study site	# points	plot years	average	standard deviation	CV (%)
MT.RAE AREA					
K2	7	35	0.68	0.37	54
Paradise V.	4	8	0.65	0.65	100
Ptarmigan R.	6	18	0.75	0.27	36
Tombstone	6	12	0.52	0.34	65
MT.ALLAN AREA					
L.Ireland	6	15	0.81	0.52	64
M.Cirque	9	25	1.18	0.75	64
PARKERS RIDGE AREA					
L.Parkers R.	9	18	0.79	0.60	84

Table 6.19 : Coefficient of variation of volumetric movement rates (cm^3/cm/year).

study site	# points	plot years	average	standard deviation	CV (%)
MT.RAE AREA					
K2	6	22	11.59	7.50	65
Paradise V.	4	7	10.11	11.40	113
Ptarmigan R.	6	18	11.26	7.36	65
Tombstone	6	8	12.75	5.09	40
MT.ALLAN AREA					
L.Ireland	6	17	16.38	10.01	61
M.Cirque	9	23	19.78	21.64	109
PARKERS RIDGE AREA					
L.Parkers R.	9	18	15.03	8.87	59

However, because few of the computed coefficients of variation had standard deviations in excess of the local mean movements (ie. CV's > 100%), these differences were not large enough to be considered statistically significant. This latter point was in fact predicted by the log-normal model employed previously (see Section 6.3.3.1). Based on these relationships, it is clear that, while there was some spatial variation in the rates of solifluction from site to site, these differences do not appear to vary significantly from the computed average rates of solifluction movement within each study area.

The second result of this analysis of solifluction at the different study sites relates to their temporal variability. Annual surveys of soil movements at the principal study sites demonstrated the pervasiveness of year to year rate changes over the study period. Table 6.20 summarizes the fluctuations of surface movement rates from one measurement period to the next. At K2, for instance, mean surface movements ranged from 0.75 cm/year in 1980-1981 to 0.45 cm/year in 1982-1983. Volumetric rates show similar patterns of short-term variability (Table 6.21), providing evidence of annual changes in the volume of sediment transported of up to 250 percent.

However, in spite of these year to year fluctuations, at a given study site mean movement showed little variability when compared on an annual basis. For example, the measured within-site coefficients of surface movements at K2 ranged from only 29 percent to 53 percent (Table 6.20). In the same period, solifluction at the other study sites in the Mt.Rae area demonstrated similar trends, with the annual coefficient values tending to be similar from year to year. As a consequence of this observation, it was assumed, first, that the mechanisms responsible for solifluction were similar over the study period, because they appeared to influence solifluction consistently. Secondly, with the notable exception of volumetric movements at the Main Cirque study site in the Mt.Allan area (Table 6.21), no significant year to year variations in solifluction rates were detected at any of the study sites over the short-term of this study period.

Table 6.20 : Annual surface movements (cm/year) by study site.

study site	1980-1981		1981-1982		1982-1983	
	mean	CV[1]	mean	CV	mean	CV
MT.RAE AREA						
K2	0.75	39	0.69	53	0.45	41
Paradise Valley	0.79	95	0.64	74		
Ptarmigan Ridge	0.94	40	0.74	29	0.66	23
Tombstone Valley	0.54	48	0.38	81		
MT.ALLAN AREA						
Little Ireland	0.79	31	0.79	31	1.13	47
Main Cirque	1.51	57	1.16	66	0.93	76
PARKERS RIDGE AREA						
Parkers Ridge			0.70	62	0.98	81

1. CV = coefficient of variability.

Table 6.21 : Annual volumetric transport (cm^3/cm/year) by study site.

study site	1980-1981		1981-1982		1982-1983	
	mean	CV[1]	mean	CV	mean	CV
MT.RAE AREA						
K2	13.58	59	10.71	72	6.65	72
Paradise Valley	12.08	75	11.66	119		
Ptarmigan Ridge	14.99	65	13.04	46	9.44	58
Tombstone Valley	13.22	49	9.61	52		
MT.ALLAN AREA						
Little Ireland	17.00	74	16.07	72	16.92	58
Main Cirque	35.74	78	22.81	92	14.40	113
PARKERS RIDGE AREA						
Parkers Ridge			14.24	52	15.83	67

1. CV = coefficient of variability.

6.3.4 Summary

The results of these analyses suggest that the mean rate of solifluction varied only slightly throughout the field area over the study period. For the most part, the wide range in the activity was found to be associated with the overall effect of a few high movements at particular lobes and did not reflect significant dimensional variations in the average magnitude described by the process measurements.

The movement data collected within each of the study sites and study areas showed little variation when compared on an areal basis. Displacements measured at the different lobes proved to be of similar magnitudes within each of the study sites. Only rarely were individual movements recorded which were greater than the local standard deviation. Similarly, the movement data indicated an insignificant amount of spatial variation when summarized and compared by study area. Taken together, these results demonstrate that the magnitude of solifluction throughout the field area was similar over the study period.

These displacement analyses were extended to examine the temporal variability of solifluction over the term of this study. The results obtained suggest there was little temporal variability in these displacements, either at each study site or within each study area. Accordingly, the mean values of displacement established over the entire study period are considered to be representative of the rate of solifluction within the field area.

In light of the above results, it is clear that the geometric mean provides the best descriptor of the *average* rate of solifluction within the field area. Thus the geometric mean rate of surface activity within this region was 0.61 ± 0.21 cm/year (Table 6.10), while the geometric mean quantity of sediment transported downslope by solifluction processes within this region was 8.67 ± 3.57 cm^3/cm/year over the same period (Table 6.11).

6.4 Conclusions

Monitoring of present-day solifluction occurring at three locations within the Alberta Rocky Mountains established two things. First, it demonstrated that solifluction was an active process within this region. Secondly, it demonstrated that the amount of sediment transported by solifluction on an annual basis was considerable and that the magnitude of this activity was probably similar through this region. In fact, the evidence suggests there was no significant variation in the rate of solifluction within the field area over the study period.

7. CONTEMPORARY SOLIFLUCTION ACTIVITY : MECHANISMS

7.1 Introduction

Solifluction is largely the product of two mechanisms, frost creep and gelifluction. This chapter presents the results and observations of a series of investigations designed to distinguish the relative importance of these two mechanisms to contemporary solifluction movements within the Alberta Rocky Mountains. The contribution of frost creep was evaluated by an examination of frost heave at two sites in the Mt.Rae area. In view of the practical difficulties involved in measuring gelifluction (c.f. Washburn, 1967; Gamper, 1981), no attempt was made to identify this component of solifluction. Instead, it was anticipated that the magnitude of this contribution could be estimated by subtracting the potential frost creep calculation from the measurements of total solifluction (c.f. C.Harris, 1972:170; 1977:41).

7.2 Frost Creep

Frost creep is an important component of solifluction movement. Unfortunately, the nature of soil displacements due to frost heave and subsidence have not, previously, been adequately evaluated in the western Canadian cordillera. S.Harris (1971, 1973) attempted to establish the character of heaving patterns associated with soil creep in several areas of the southern Rockies, but met with only limited success. Investigations by Mackay and Matthews (1974b) in the mountains of southern British Columbia indicated that frost heaving was locally insignificant. However, illustrations of significant heave displacements from elsewhere in the North American cordillera (Benedict, 1970; Fahey, 1971, 1973, 1974) demonstrate that frost creep can be an important transport mechanism.

7.2.1 Frost Heaving Mechanisms

The smallest fraction of frost heave is due to volumetric increases caused by the freezing of *in situ* pore water (Anderson, et. al., 1978). At a maximum this accounts for soil expansion of approximately 9 percent (Taber, 1930), although it is usually somewhat less than this because of the varying physical properties of soils (Sayward, 1979). The bulk of frost heave is due to the growth of ice lenses along the freezing front. For this to occur thermal/flux imbalances must be established to initiate the migration of soil water to the freezing front interface (Forland and Ratkje, 1980; Fahey and Thompson, 1982). Continued advance of the freezing plane results in rhythmic ice lensing and large volumetric soil expansion (Takagi, 1979, 1980; Konrad and Morgenstern, 1980). The intrinsic controls most important in defining frost heave characteristics are the rate of advance of the freezing plane, the physical properties of the soil, and the availability of soil moisture (Miller, 1972; Fahey, 1979).

7.2.2 Study Sites

In this study, evaluations of frost heave displacements were carried out at sites in Mt.Rae area. These investigations were completed using frost heave bedsteads installed in July, 1980. Bedstead A, located at the Highwood Ridge site (see Figure 4.4) at 2340 m asl., was positioned within an area of active frost boils (D.Smith. 1979:142) surrounded by a broken vegetation carapace dominated by *Salix arctica*, *Potentilla diversifoila* and *Poa arctica*. Sediments at the site are classified as highly frost susceptible silts having moderate liquid limits (45 percent) and a wide plasticity index (18 percent).

Bedstead B, installed at the K2 study site (see Figure 4.4), was located among a field of solifluction lobes at 2440 m asl (see Figure 4.9). This site is characterized by a late-lying snowpack and a *Salix arctica*, *Silene acaulis* and *Poa arctica* plant community. Sediments at the site are classified as silty-sands having low liquid limits (32 percent) and limited plasticity (less than 5 percent).

7.2.3 Methodology

The two frost heave bedsteads constructed for these investigations were similar in design to those described by C.Harris (1971), but incorporated modifications suggested by

B.Matthews (1967) and James (1971) to provide a temporal-event record. Each bedstead consisted of a metal cross-piece bolted to a pair of steel legs firmly rooted 1 m below the ground surface (Figure 7.1). A set of five aluminum heave rods passed vertically through this frame, remaining free to move up and down with the heaving soil. Weekly measurements of the rod heights above the frame during the primary field season were averaged to describe vertical displacements occurring along the 1 m transect. Observations were discontinued at Bedstead B over the winter period when the site was inaccessible, but were continued at monthly intervals at Bedstead A.

A shielded Lambrecht thermograph mounted at one end of the bedstead provided a continuous record of air temperature and soil displacement. The latter was achieved by modifying the instrument so that a sixth heave rod was linked directly to a pen arm. Temporal surface displacements from this rod were recorded on the rotating drum.

A record of monthly soil temperature and moisture conditions was gathered at both bedstead sites using strings of SoilTest fiberglass soil moisture-temperature cells (SoilTest, 1975), installed in 1980. Four cells, at 5, 25, 50 and 75 cm depths, were read biweekly during the summer field season and monthly at Bedstead A over the winter months.

7.2.4 Results

Observations of frost heave patterns indicated the activity of both diurnal and seasonal processes. Diurnal frost heave occurred in response to nocturnal invasions of a shallow freezing plane into the soil (Outcalt, 1970; Soons and Greenland, 1970); while seasonal frost heaving accompanied penetration of the annual freezing plane (Fahey, 1974, 1979). The temporal spacing of these events and their differential impact enjoins separate discussion.

7.2.4.1 Diurnal Frost Heaving

Diurnal frost heaving occurs when nocturnal segregation ice causes a frozen cap of soil to be raised above an unfrozen soil surface (Sayward, 1979; Meentemeyer and Zippin, 1980). Various field and laboratory studies have shown that this process occurs only within narrow

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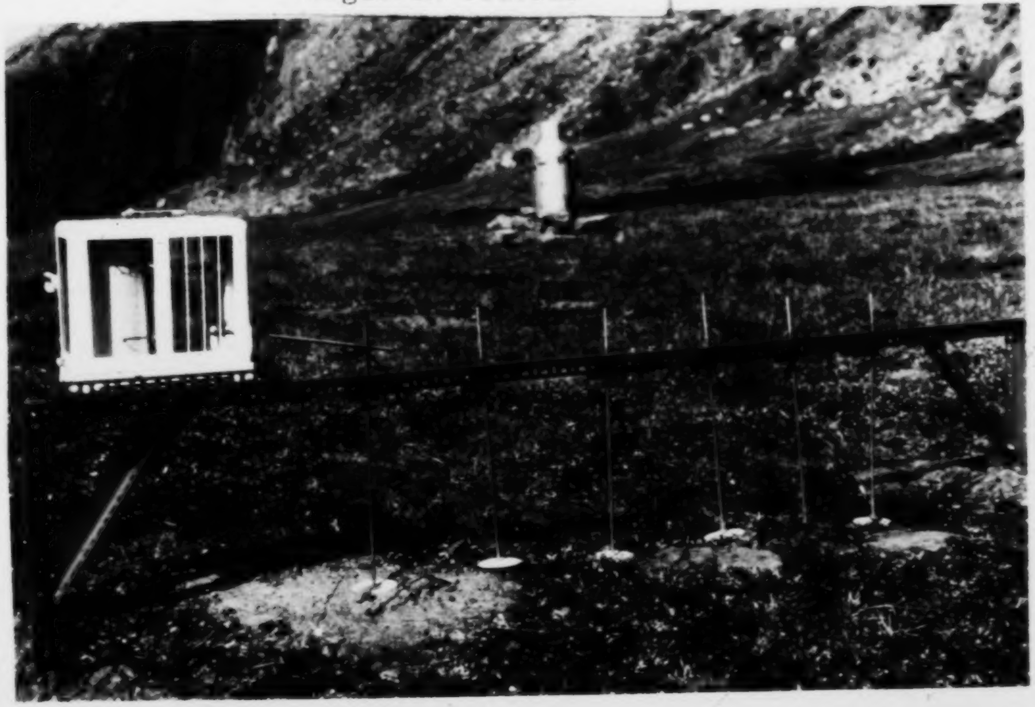

Figure 7.1 : Frost heave bedstead (Bedstead A) on Highwood Ridge. Note that the protective shield which encased the attached thermograph has been removed to allow for inspection. Pictured in the background is a Belfort recording rain gauge.

microclimatic and soil textural ranges (Higashi and Corte, 1971; Meentemeyer and Zippin, 1981). Following Fahey (1973:56), a diurnal frost heave cycle in this study was taken to constitute a rise and collapse event which occurred within a 24 hour period.

Figure 7.2 shows a series of typical diurnal frost heave cycles recorded concurrently at the two sites. On average, these events had a ten hour duration, with heaving during the first eight hours and settling during the remaining two. These cycles tended to start between 2200 to 0200 hours, with maximum heave occurring by 0800 hours. The maximum diurnal heave recorded was 16.5 mm, but average heave tended to be less than 10 mm.

Table 7.1 summarizes the diurnal frost heave record obtained at the two bedstead sites. In addition, it presents the corresponding record of freeze-thaw cycles noted in the air at each site. Unlike the freeze-thaw cycles which were observed to have a bimodal distribution, the frost heave cycles illustrated a single period of peak frequency. At both sites over 70 percent of the frost heave cycles occurred in the August to October period, with 30 percent observed in September alone. This disparity reflects the presence of an insulating snowcover and seasonally frozen soil in the early season freeze-thaw period. Table 7.1 also demonstrates that considerable inter-annual variations in diurnal frost heave events were fairly commonplace. For instance, almost twice as many events were recorded in 1980 compared to 1981 and 1982.

Discussion

These investigations demonstrated the activity of diurnal frost heave processes in the Mt.Rae area. Frequent observations of individual events at both bedsteads confirmed they were essentially a surface phenomenon associated with the growth of needle-ice (Brockie, 1967; Soons and Greenland, 1970). With an average of only 20 events per year, their potential impact on solifluction is limited.

It is likely, however, that these events were of consequence to ancillary slope processes. First, surface disturbances of this nature reduce soil strength (Caine, 1978b) promoting erosion by water (Soons, 1967; Soons and Rayner, 1968) and wind (Troll, 1973a; Beaty, 1974; Hall, 1979). Second, diurnal heave and settlement of surface soils itself results in their downslope

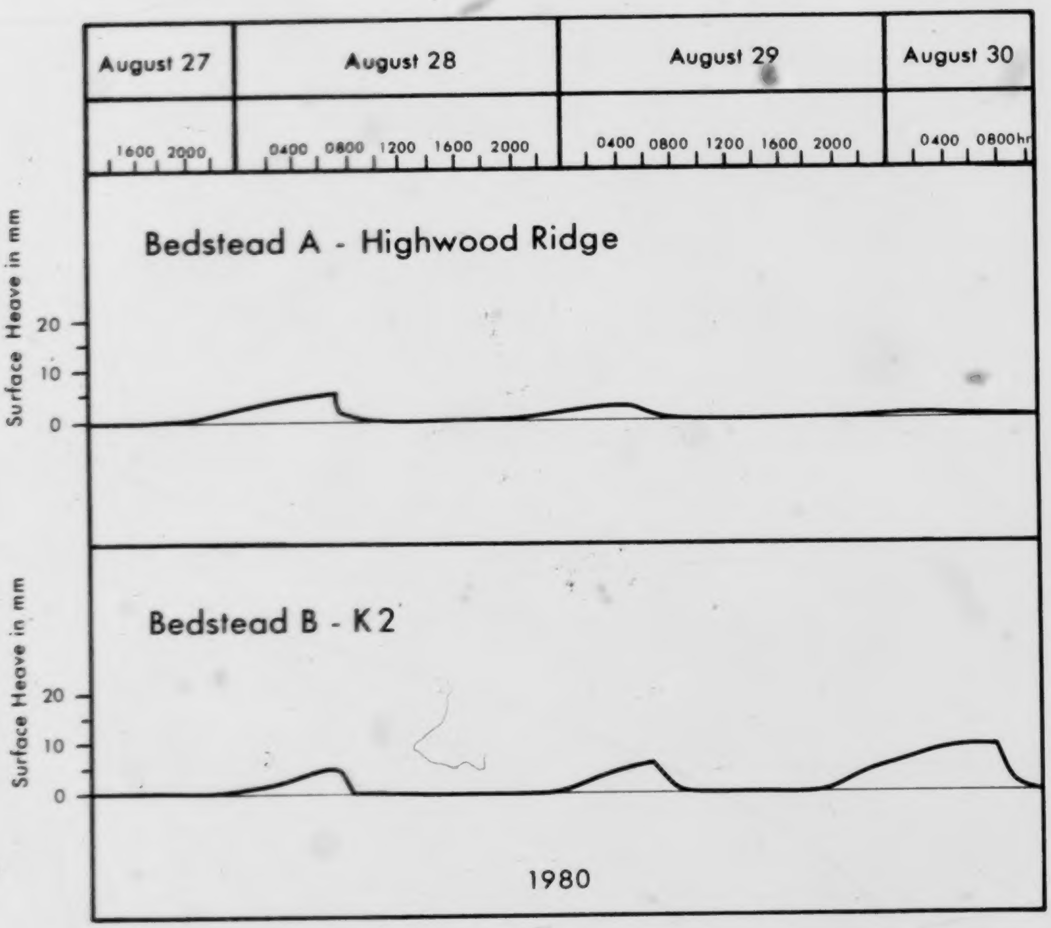

Figure 7.2 : An example of the diurnal frost heave record recorded at the two bedstead sites.

Table 7.1 : Monthly totals of freeze-thaw cycles in the air (A) and frost heave cycles at the surface (B).

		HIGHWOOD RIDGE		K2	
year	month	A	B	A	B
1980	July	3[1]	0[1]	2[1]	2[1]
	August	16	9	9[1]	9[1]
	September	22	10	17	9
	October	14	8	11	8
	November	3	1	3	0
	December	nd[2]	0	nd	0
1981	January	nd	0	nd	0
	February	nd	0	nd	0
	March	nd	0	nd	0
	April	nd	0	nd	0
	May	nd	0	nd	0
	June	9[1]	4[1]	nd	1
	July	11	6	12	3
	August	2	0	2	1
	September	11	2	15	6
	October	16	5	12	0
	November	10	3	6	0
	December	0	0	nd	0
1982	January	0	0	nd	0
	February	nd	0	nd	0
	March	nd	0	nd	0
	April	nd	0	nd	0
	May	nd	nd	nd	0
	June	2	2	0[1]	0[1]
	July	6	6	4	4
	August	4	3	2[1]	2[1]
	September	8	8	nd	nd
	October	5	3	nd	nd
	November	2	1	nd	nd
	TOTAL	146	73	95	44

1. incomplete monthly record.
2. nd = no data.

transport (Higashi and Corte, 1971), although this activity is generally considered to be an insignificant component of mass wasting in general (c.f. Meentemeyer and Zippin, 1980).

In summary, it was clear from these investigations that diurnal frost heave cycles played an insignificant role in the promotion of solifluction, although these events likely encouraged other slope processes.

7.2.4.2 Seasonal Frost Heaving

Seasonal frost heaving accompanied prolonged periods of winter frost penetration into the ground; while ground subsidence was concomitant with ground thaw in the primary melt season. Figure 7.3 illustrates the seasonal soil displacements measured at the two bedsteads in 1980-1982.

Frost heave and subsidence

Examination of Figure 7.3 suggests that the greatest percentage of seasonal heave occurred between September and November, with the greatest rates of heave experienced in October (Table 7.2). However, heaving in the winter of 1980-1981 apparently continued until early January on Highwood Ridge. Heaving was succeeded by a lengthy period of stabilization over the winter months, followed by a brief resurgence in heaving during the initial stages of ground thaw. The latter events were attributed to contributions of atmospheric moisture and meltwater to surface soils. Average maximum cumulative heave at both sites amounted to 4.5 cm in 1980-1981.

Magnitudes and patterns of heaving in the 1981-1982 period differed markedly from the previous season. At the Highwood Ridge site the displacements achieved by mid October persisted over most of the winter. Similar to the previous year, a moderate increase in total heave was observed just prior to seasonal subsidence. Maximum average cumulative heave at Bedstead A in 1981-1982 was only 2.3 cm. The pattern of heave at Bedstead B was less clearly defined due to the inability to visit the site over the winter months. However, cumulative heave values recorded prior to melt of the winter snowpack were 3.4 cm. These values were 75 percent

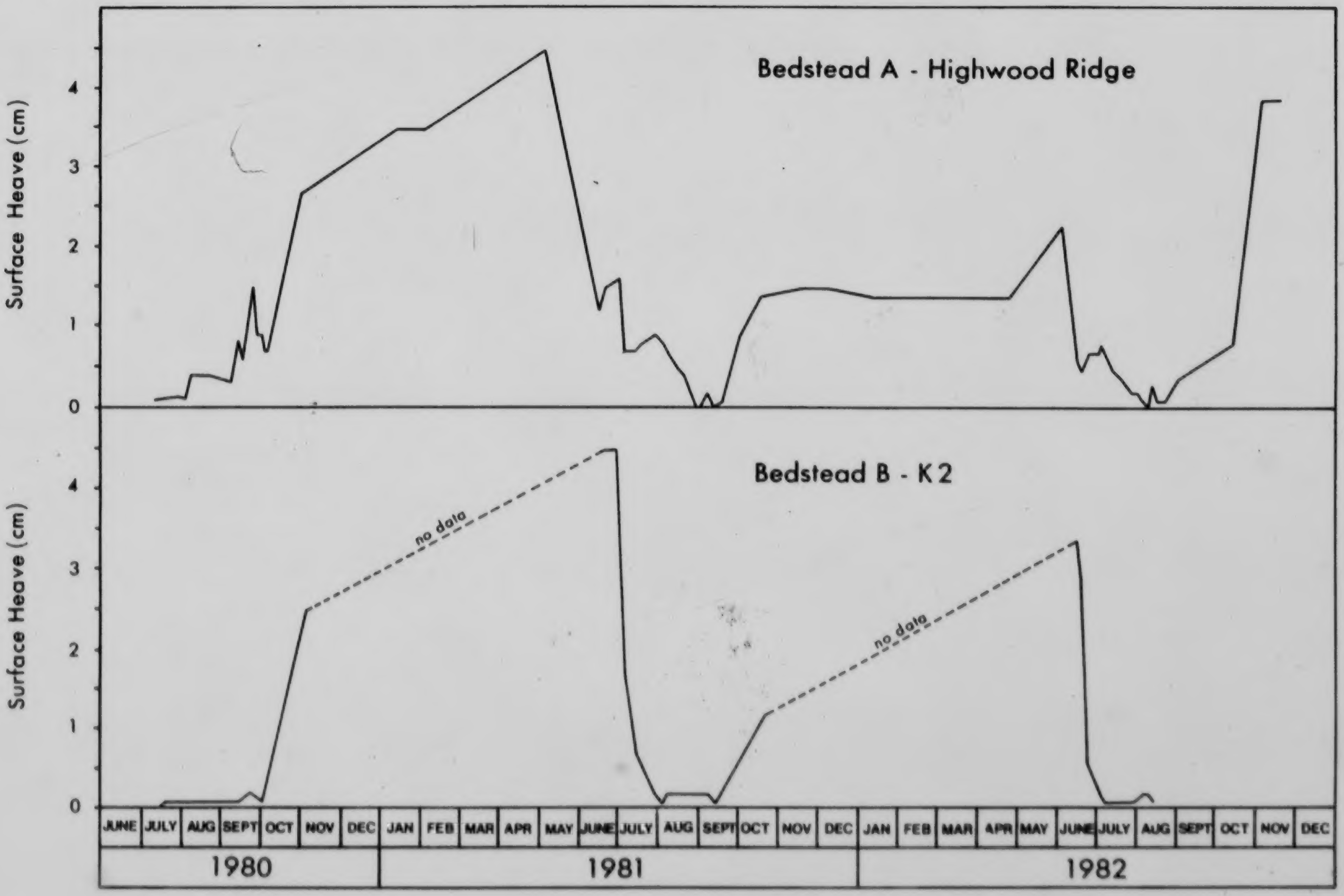

Figure 7.3 : Seasonal frost heave record recorded at the two frost heave bedsteads.

Table 7.2 : Average daily heave and settlement rates at Bedstead A and B, 1980-1983[1].

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
BEDSTEAD A												
1980							0.00	0.00	0.30	0.58	0.27	0.00
1981	0.00	0.00	0.00	0.00	0.23	-1.10	-0.16	0.00	0.27	0.16	0.03	0.00
1982	0.00	0.00	0.00	0.00	0.29	-0.53	-0.16	0.00	0.16	1.00	0.00	0.00
1983	0.00	0.00	0.00	0.00	0.00							
BEDSTEAD B												
1980							0.00	0.00	0.00	0.03	0.80	
1981						0.00	-1.45	0.00	0.10	0.29	0.27	
1982						-0.93	-0.13	0.00				

1. positive values are net monthly heave (mm/day), negative values are net monthly settlement (mm/day).

of those reached in the previous season and indicate a similar heave regime.

Observations in the 1982-1983 heave season were made only at Bedstead A. Seasonal heave began on October 16 and was completed by the first week of November. Cumulative heave to that point averaged 3.9 cm. A subsequent visit to the site on May 17, 1983, suggested only insignificant changes in heave magnitudes over the intervening winter months.

Comparison of heave magnitudes at the Highwood Ridge site indicated that, on average, about 75 percent of the annual seasonal heave occurred by the end of November. The mean rate of heave during this period was on the order of 0.31 mm/day. However, an order of magnitude separated maximum and minimum values (Table 7.2). The maximum rate of heave occurred in a three week period of 1982, when 1.7 mm/day of heave was noted.

In addition to heaving patterns, Figure 7.3 also demonstrates the rapid subsidence which characterized thawing of these uplifted soils. At Bedstead A settlement was frequently interrupted by temporary refreezing and further swelling of the soil. The abrupt rate of settlement at Bedstead B was a reflection of the late-lying snowpack. This delayed subsurface melt until the early summer, when diurnal air temperatures above 0.0° C ensured rapid thaw of the ground. Comparison of settlement rates from the two sites indicates they tended to be much greater at the K2 site (Table 7.2), where the rates of settlement averaged 0.8 mm/day but attained maximum values of 4.6 mm/day.

Frost penetration and thawing

The monthly soil temperature fluctuations at the two bedstead sites, monitored using the soil moisture-temperature cells, are summarized in Table 7.3. They indicate decreasing temperature with depth below the soil surface in the snow-free summer months, with reverse temperature gradients during the winter. It is apparent, though, that sediments at Bedstead B experienced a much shorter frost-free period due to their delayed seasonal thaw.

Annual variations in thermal regimes at Bedstead A are presented in Figure 7.4. The winter period of 1980-1981 was characterized by frequent ambient air temperature shifts around 0.0° C. In combination with significant snowfall accumulations early in the season, these relatively warm air temperatures resulted in a slow advance of the freezing front (5 mm/day) and the persistence of relatively warm subsurface temperatures. More extreme climatic conditions in 1981-1982 resulted in rapid penetration of the 0.0° C isotherm (11.0 mm/day) and the development of lower subsurface temperatures. In 1982-1983, following a rapid decline in air temperatures in mid October, the greatest rate of advance of the frost line was recorded (25 mm/day).

Thaw penetration rates during the spring melt period were estimated from subsurface isotherms. Following the rapid rise of mean daily air temperatures in April and May at Bedstead A, diurnal thaw and nocturnal refreezing of the uppermost soil layers were frequently

Table 7.3 : Monthly soil temperatures (°C) at frost heave bedsteads, Mt.Rae area, 1980-1982.

	BEDSTEAD A				BEDSTEAD B			
month	5.0[1]	25.0	50.0	75.0	5.0	25.0	50.0	75.0
1980								
July	5.8	4.8	3.4	0.4				
Aug	6.1	6.5	4.1	2.2	2.8	3.8	3.5	2.8
Sept	1.9	1.5	1.8	1.3	1.5	2.1	2.3	2.0
Oct	0.0	0.8	1.3	0.6	0.3	0.5	1.0	1.0
Nov	-0.5	0.5	1.0	1.0	0.0	0.0	1.5	1.0
Dec								
1981								
Jan	-2.0	-2.0	-1.0	0.0				
Feb	-4.0	-3.0	-1.5	-1.0				
Mar								
Apr								
May	0.0	0.0	0.0	0.0				
Jun	1.2	1.0	1.0	0.6				
Jul	6.3	3.7	3.4	0.8	4.4	1.8	1.6	1.0
Aug	10.5	8.3	8.0	4.5	11.1	8.1	6.7	2.7
Sep	6.3	5.1	5.0	3.8	6.0	7.3	7.3	6.0
Oct	-0.5	0.0	1.2	1.2	0.0	1.0	2.0	2.0
Nov	-2.0	-1.0	0.5	1.0				
Dec	-6.0	-4.0	-3.5	-1.0				
1982								
Jan	-8.0	-5.0	-4.0	-4.0				
Feb								
Mar								
Apr	-3.0	-3.0	-2.5	-2.5				
May								
Jun	7.4	4.4	2.0	0.3	2.5	0.4	0.6	0.7
Jul	8.3	6.1	4.7	2.2	5.9	3.5	2.1	1.0
Aug	8.2	6.4	5.9	4.0	7.1	6.7	5.8	4.3
Sep	4.5	4.7	4.3	3.0				
Oct	1.0	1.5	2.5	2.0				
Nov	-3.0	-2.0	0.0	0.8				

1. depth below ground surface in cm.

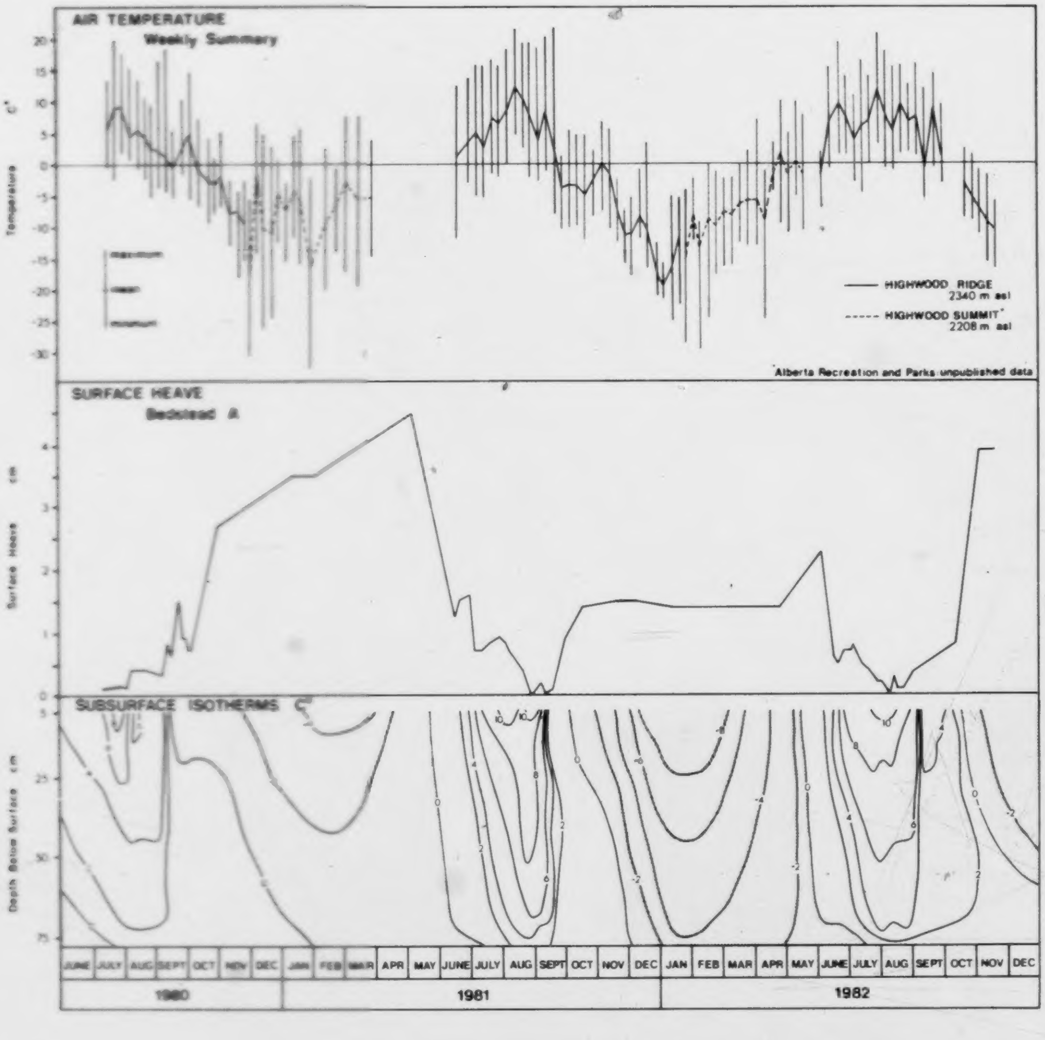

Figure 7.4 : Air temperature, frost heave and soil temperature at the Highwood Ridge bedstead site (1980-1982).

indicated. By mid June descent of the thaw line was rapid, often by as much as 10 to 20 mm/day. At Bedstead B, where snowmelt begins almost a month later, thaw rates were even faster. In the 1981 and 1982 thaw seasons, rates of melt averaged between 45 to 52 mm/day.

Discussion

The magnitudes of frost heave recorded in the Mt.Rae area are comparable to those measured at many other locations of active solifluction (C.Harris, 1972; Kaiser, 1980; Gamper, 1981). Clearly though this is not a universal characteristic, as observations by Everett (1967), Benedict (1970) and Fahey (1971, 1974) describe solifluction sites which experience much greater displacements.

In this study frost heave appeared to be greatly influenced by soil water variations. Soil moisture percentages recorded at the two bedstead sites, using the soil moisture-temperature cells, are presented in Table 7.4. The data suggest both sites experienced similar soil moisture conditions, with the greatest soil-water present immediately after the ground thawed. Gradual drying over the summer season progressively depleted the water content of the soil above 75 cm. Evidence of unusual soil drying in 1981, particularly at Bedstead A, was apparent when compared to soil moisture conditions in 1980 and 1982. In addition, there was an indication of near-surface soil moisture recharge during the early fall period.

In the present context, the most significant of these soil water fluctuations were the annual variations in pre-freeze soil moisture regimes. As Figure 7.5 shows, soil moisture percentages over the summer of 1981 were much lower than those in the preceding or following seasons at Bedstead A. This was particularly true of the uppermost soil horizons between 5 and 25 cm, where the amount of soil moisture present was about 22 percent less than that measured in the preceding (1980) and following (1983) prefreeze September periods (Table 7.4).

The amount of frost heaving was also dependent upon the rate of soil freezing (c.f. Penner, 1972; Penner and Walton, 1979). As Figure 7.6 shows, large annual variations in this relationship were observed at Bedstead A. For instance, at the beginning of the 1980-1981 season each 10 cm of frost penetration generated about 1 cm of surface heave; whereas in

Table 7.4 : Monthly soil moisture content (%) at bedsteads, Mt.Rae area, 1980-1982.

	BEDSTEAD A				BEDSTEAD B			
month	5.0[1]	25.0	50.0	75.0	5.0	25.0	50.0	75.0
1980								
Jul	33	nd[2]	23	22	nd	nd	nd	nd
Aug	44	21	24	34	28	25	40	25
Sep	29	26	25	37	26	24	39	25
Oct	25	26	25	37	29	26	39	25
1981								
Jun	42	26	+[3]	+	+	+	+	+
Jul	37	26	34	26	44	30	28	25
Aug	31	24	34	28	39	25	39	26
Sep	23	19	22	23	24	23	39	24
Oct	22	18	19	33	+	23	37	23
1982								
Jun	38	+	+	+	44	+	+	+
Jul	34	22	25	37	32	28	40	26
Aug	32	21	24	37	29	24	38	28
Sep	30	23	26	37	nd	nd	nd	nd
Oct	36	24	27	37	nd	nd	nd	nd

1. depth below ground surface in cm.
2. nd = no data.
3. + = frozen soil.

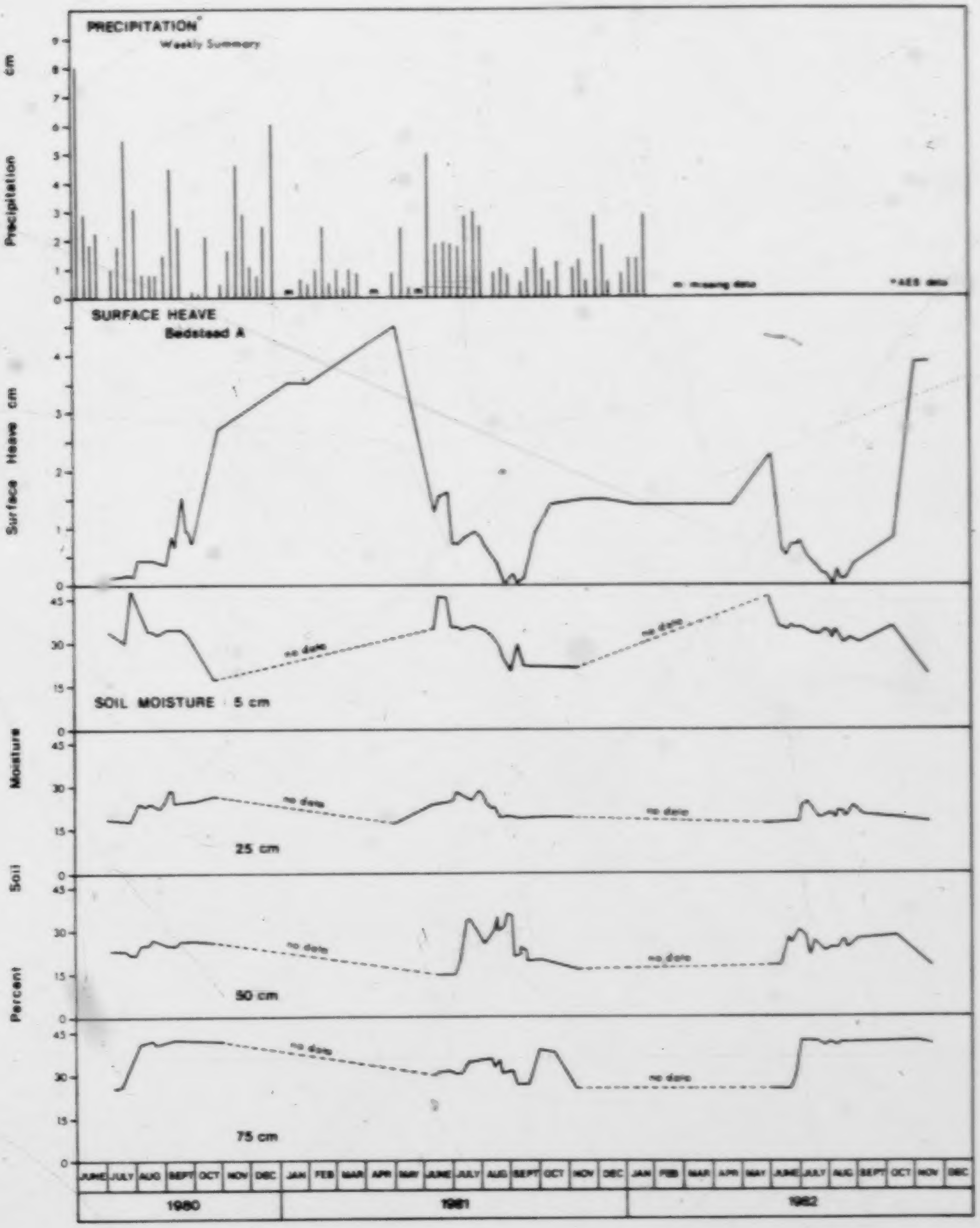

Figure 7.5 : Precipitation, frost heave and soil moisture at the Highwood Ridge bedstead site (1980-1982).

1982-1983 only about 0.5 cm of heave was produced by the same penetration increment. Examination of Figure 7.4 suggests part of the explanation of this behavior relates to the differing thermal conditions between the two seasons. Rapid penetration of the freezing plane in 1982-1983 likely inhibited moisture migration and thereby diminished the potential for frost heaving (c.f. Konrad, 1980; Farouki, 1981). Conversely, in 1980-1981 a more slowly advancing freezing front (Figure 7.4) provided a longer period conducive to ice segregation.

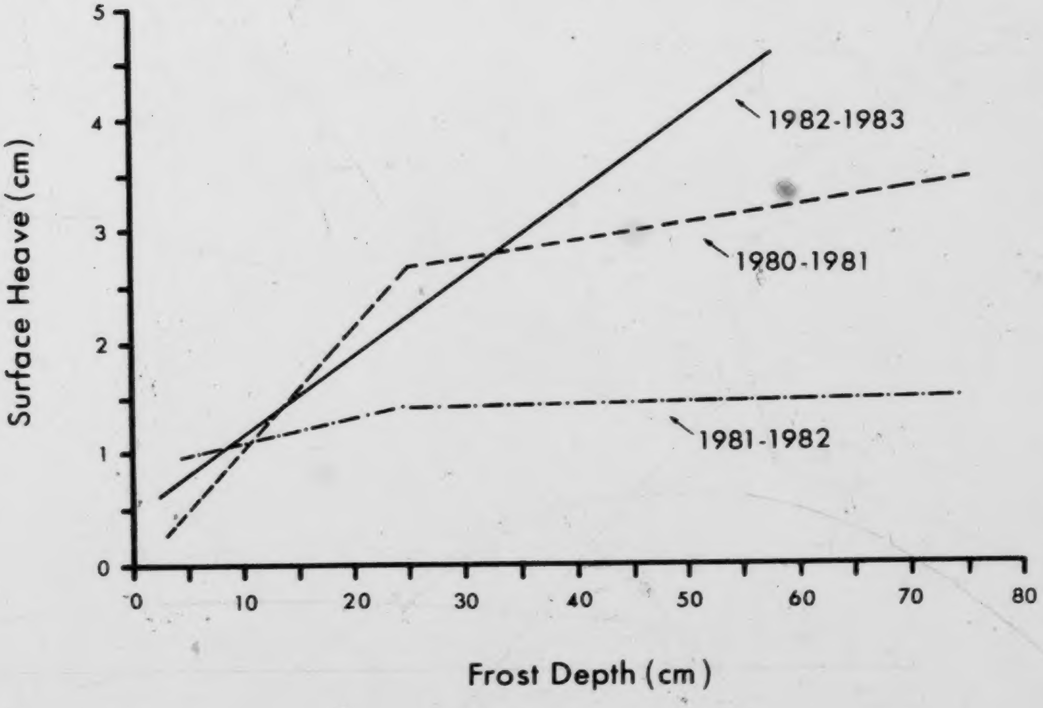

Figure 7.6 : Relationship between the depth of frost penetration and frost heaving at Bedstead A (1980-1983).

Support for these conclusions is evident when the seasonal relationship between frost heave and penetration is examined in detail. In 1981-1982 virtually all of the surface heave occurred in response to freezing of only the upper 25 cm of sediment (Figure 7.4), while further penetration of the freezing plane resulted in little additional heave (Figure 7.6). Similarly, in 1980-1981, approximately 77 percent of the total amount of seasonal heave occurred by November 4 when only the upper 25 cm of soil had frozen (Figure 7.4). Although later advances of the freezing plane resulted in additional heave, it was of a much smaller magnitude (Figure 7.6). Presumably this resulted when slow penetration of the freezing plane allowed moisture time to travel from deeper layers and thereby contribute to near-surface ice lens growth (c.f. Takagi, 1979; Morgeau and Morgenstern, 1980). As a consequence, the lower layers of sediment were depleted of soil-water and experienced little soil bulking when they subsequently froze. In fact, there is some evidence that the lowermost soil horizons at Bedstead A experienced soil-water losses as the upper soil froze in both 1980-1981 and 1981-1982. This is evident when the amount of soil moisture present at 75 cm prior to the freeze-up is compared to the amount present immediately upon thawing in the following spring (Figure 7.5). In both seasons, a substantial loss is evident.

This relationship between the rate of soil freezing and frost penetration-heave was underscored in the 1982-1983 season. During that period, the frost plane advanced to approximately 60 cm below the ground surface in about a three week period, causing a constant rate of heave with little indication that ice lens growth was restricted to a particular horizon. This homogeneous pattern of soil-water freezing implies that moisture migration was insignificant during this particular season.

Surprisingly, only a limited degree of spatial variation was observed in the patterns of seasonal frost heaving within this area. In fact, the within-site variances in heaving magnitudes usually exceeded those between the two sites. Given the large environmental and textural differences which exist between these sites, it may be that these patterns are indicative of the general character of frost heaving within this area.

7.2.5 Potential Frost Creep

The amount of seasonal frost heaving on a slope directly influences the magnitude of frost creep. Jahn (1975:145) and C.Harris (1981a:76) have discussed the nature of this relationship, noting that potential frost creep (PFC) can be calculated assuming that:

$$\mathrm{PFC} = h \tan \theta$$

where PFC represents downslope displacement at the surface, h represents the amount of heave and $\tan \theta$ is the local slope.

The magnitude of seasonal frost heaving in the Mt.Rae area was estimated as an average value from observations completed at Bedstead A (1980-1983) and Bedstead B (1980-1982). These observations indicated that the average seasonal frost heave in the Mt.Rae area amounted to 4.5 cm in 1980-1981, 2.9 cm in 1981-1982, and 3.9 cm in 1982-1983. Following each season, resettlement of the ground saw it return to base-levels established during the first field season. While these results probably have general applicability to most of the Mt.Rae study sites, differing environmental conditions within the Mt.Allan and Parkers Ridge areas likely limit their representativeness of heave conditions within those settings. However, because frost heaving was not evaluated within either of those areas, values from the Mt.Rae area were used to provide an estimate of the potential frost creep magnitudes.

Table 7.5 summarizes the average potential frost creep estimated for each of the study sites. At all of the sites the largest potential for frost creep occurred in 1980-1981, while the smallest potential displacements occurred in 1981-1982. Nonetheless, it should be appreciated that, without further fieldwork, application of the Mt.Rae data beyond the settings in which they were measured remains suspect.

7.3 Gelifluction

It was anticipated that the contributions of gelifluction mechanisms to solifluction movement could be estimated by discounting the potential frost creep contributions. However, as Table 7.6 demonstrates, at virtually all of the study lobes the potential frost creep values, as

Table 7.5 : Estimates of potential frost creep (cm), 1980-1983[1].

Location	Tread Angle[2]	POTENTIAL FROST CREEP		
		1980 1981	1981 1982	1982 1983
MT.RAE AREA	17.6	1.43	0.73	1.24
K1	17.0	1.38	0.70	1.19
K2[3]	17.8	1.45	1.09	1.26
Paradise V.	19.8	1.62	0.82	1.40
Ptarmigan	20.0	1.63	0.83	1.42
Tombstone	11.7	0.93	0.48	0.81
MT.ALLAN AREA	28.5	2.44	1.25	2.12
L. Ireland	27.8	2.38	1.21	2.06
Main	27.4	2.33	1.19	2.02
PARKERS RIDGE	20.5		0.86	1.46
FIELD AREA	21.2	1.75	0.89	1.51

1. average frost heave derived from Bedstead A and B (1980-1983).
2. average slope angle in degrees.
3. K2 values; 1980-1982 from Bedstead B, 1982-1983 from Bedstead A.

Table 7.6 : Summary of solifluction movement and potential frost creep displacement rates (cm/year).

	1980-1981		1981-1982		1982-1983	
	SM[1]	PFC[1]	SM	PFC	SM	PFC
Mt.Rae	0.63	1.43	0.52	0.73	0.42	1.24
Mt.Allan	0.83	2.44	0.67	1.25	0.77	2.12
Parkers Ridge	--	--	0.43	0.86	0.61	1.46
FIELD AREA	0.73	1.75	0.54	0.89	0.60	1.51

1. SM = mean (geometric) solifluction movement at the surface.
2. PFC = potential frost creep.

calculated from the Mt.Rae area frost heave data, proved to be much greater than the movements which were actually recorded. In fact though, given the well-documented, site-specific nature of seasonal frost heaving (c.f. Fahey, 1974:67), the general applicability of the Mt.Rae data to all of the study sites is almost certainly questionable. However, it is also obvious, that even within the Mt.Rae area total solifluction movements were, on average, only 50 percent of those predicted by the potential frost creep model discussed previously. In view of these results, a specific gelifluction contribution could not be readily extracted from the solifluction movement data.

Despite this apparent failure to differentiate the contribution of gelifluction to solifluction movement within the field area, investigations conducted at several lobes demonstrated activity patterns which allowed for evaluation of the involvement of gelifluction mechanisms. The following sections review the results of these investigations and examine the potential role of gelifluction in solifluction morphogenesis.

7.3.1 Gelifluction Flow Mechanism

Gelifluction describes the slow, downslope transport of saturated soil under periglacial conditions (French, 1976). Active gelifluction is commonly regarded as a seasonal form of mass wasting which occurs only intermittently, primarily during the spring thaw period. It tends to be associated with thawing slopes overlying impermeable ground ice, which acts to inhibit the downward percolation of water (Williams, 1959; Derbyshire, 1977). Movement appears to take place when the soil is wettest and at its lowest strength (Chandler, 1977).

7.3.2 Experimental Sites

In order to explain the character of gelifluction within the Alberta Rockies, detailed solifluction movement studies were carried out at three turf-banked lobe sites. In the Mt.Rae area, Lobe 10, located at the K2 study site, was identified for detailed study in 1980 (see Figure 4.4). In the Mt.Allan area, the gelifluction research focused on Lobe 37 situated within the

Main Cirque study site (see Figure 4.12). Two adjacent lobes, Lobes 50 and 51, were selected for detailed monitoring in 1981 at Parkers Ridge (see Figure 4.16). To identify the patterns of solifluction at these lobes all three of the monitoring devices discussed previously were utilized. However, in order to obtain a broader perspective on the patterns of solifluction at each plot, these devices were established in higher frequency clusters than was the case at most of the lobes.

7.3.2.1 Lobe 10

Lobe 10 is located at the northwest-facing K2 study site at 2422 m asl in the Mt.Rae area. Situated immediately downslope of the frost creep evaluation site at Bedstead B (see Figure 4.9), this moderately sized lobe (approximately 5.06 m^3 in volume) is composed primarily of weathered sandy-silt colluvium (see Table 5.6). It has a steep riser thickly mantled by *Salix reticulata*. The adjacent tread and parent slope are only sparsely vegetated by a *Salix arctica / Juncus drummondii* plant community. While the snowpack commonly clears this plot by late June, surface meltwaters, derived from an upslope melting snowpack, continue to wash across the site throughout most of July.

Monitoring of solifluction at Lobe 10 was initiated in 1977 when a dowel pillar column was installed on the tread surface. Soil displacements measured by this column were estimated when the column was exposed in 1982 to examine soil movements over the intervening years (see Figure 6.2). In 1980 an inclinometer tube and an 18-point painted stone network were added to this site. Annual surveys of solifluction recorded by the tube (see Figure 6.1) and the painted stones were terminated after the 1983 field season.

Results

The results of these surveys of solifluction displacement at Lobe 10 are summarized in Table 7.7. They demonstrate that the average rate of surface movement at this plot had considerable local variability, ranging from 0.0 cm/year in the vicinity of the frontal snout at point 7, to a maximum velocity of 1.27 cm/year some 2.50 m behind the lobe front at point 16.

However, these results demonstrate that the most rapid solifluction movements at Lobe 10 were concentrated at positions adjacent to the lobe axis. This was particularly evident in 1981-1982, when a tongue of relatively rapidly moving sediment was transported along the lobe axis to abut the lobe riser (Figure 7.7). While this displacement pattern was much less apparent over the following 1982-1983 measurement period, a similar pattern of concentrated movement was recorded (Figure 7.7). Reductions in these relatively high movement rates, as the lobe front was approached, suggests that this lobe riser was acting as a soil dam and impounding these quickly moving sediments. The fact that vertical velocity profiles, established in close proximity to the snout (see Figures 6.1 and 6.2) showed relatively shallow movements, suggests this lobe

Table 7.7 : Average annual surface movements per point at Lobe 10.

point	period	position	mov't cm/year	method[1]
1	1980-1983	riser	0.00	ps
2	1980-1983	riser	0.01	ps
3	1980-1983	tread	0.05	ps
4	1980-1983	riser	0.13	ps
5	1980-1983	riser	0.23	ps
6	1980-1983	riser	0.43	ps
7	1980-1983	riser	0.00	ps
8	1980-1983	tread	0.95	ps
9	1980-1983	slope	0.53	ps
10	1980-1983	tread	0.50	ps
11	1980-1983	slope	0.40	ps
12	missing	tread	nd[2]	ps
13	1980-1983	slope	0.20	ps
14	1980-1983	riser	0.22	ps
15	1980-1983	tread	1.10	ps
16	1980-1983	tread	1.27	ps
17	missing	tread	nd	ps
18	1980-1983	slope	0.55	ps
19	1977-1982	tread	0.74	dp
20	1981-1983	tread	0.58	it

1. ps = painted stone, dp = dowel pillar, it = inclinometer tube.
2. nd = no data

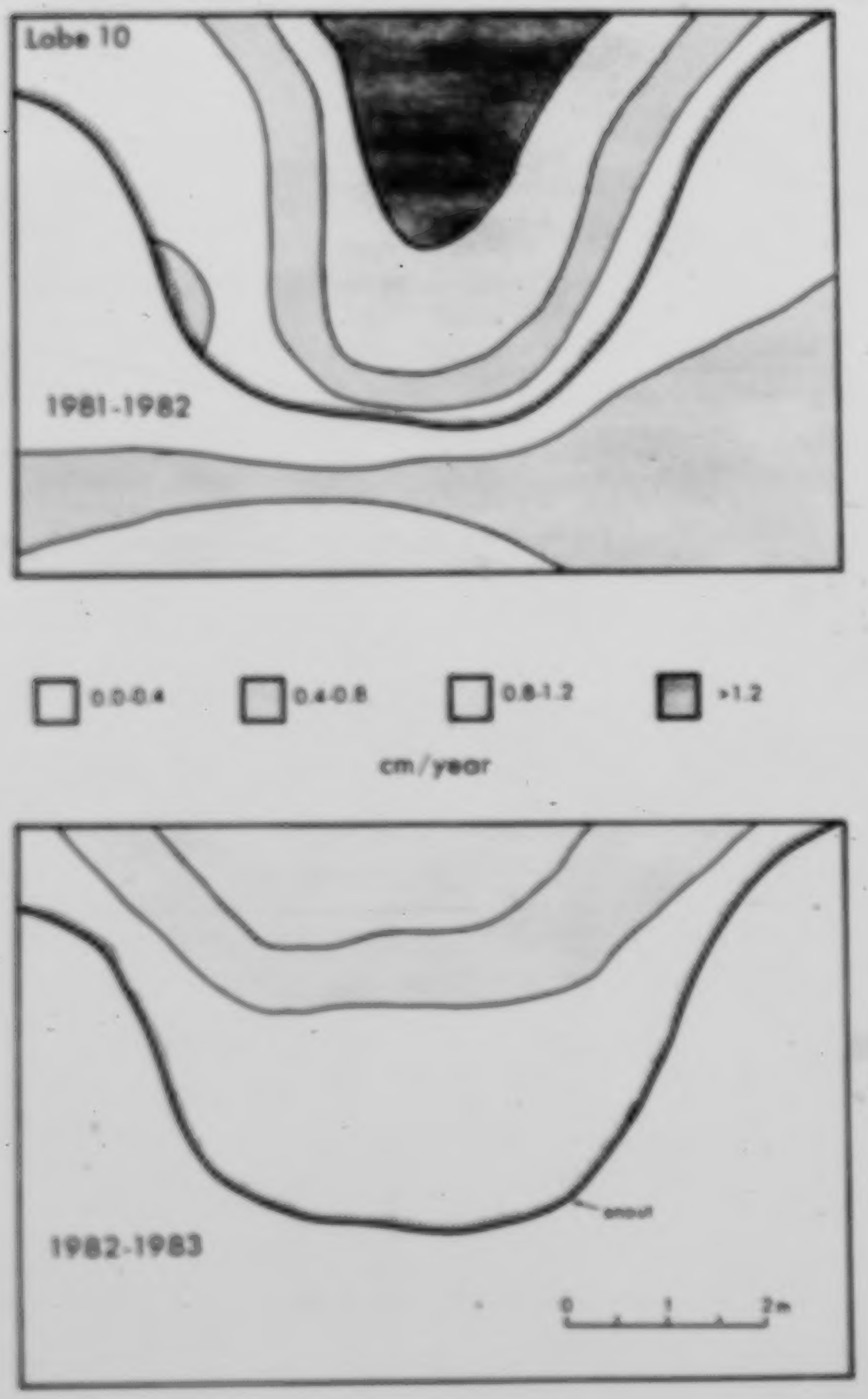
Lobe 10
1981-1982
0.0-0.4
0.4-0.8
0.8-1.2
>1.2
cm/year
1982-1983
0
1
2m

Figure 7.7 : Temporal variations in surface movement at Lobe 10, K2 study site.

must be progressively thickening as the moving soil is continually retarded behind this, essentially stable, barrier (Figure 7.7).

Evaluation of Movement Mechanisms

Unfortunately, the magnitude of the contribution gelifluction mechanisms made to the solifluction movements monitored at Lobe 10 could not readily be extracted. This was because the solifluction movements recorded in each of the field seasons were much less than the predicted potential frost creep values. This point is emphasized in Table 7.8, where the potential frost creep magnitudes calculated for Lobe 10 in each year exceed the monitored surface displacements by from 42 percent (1981-1982) to 81 percent (1982-1983). Given the magnitude of the retrograde adjustments described by this relationship, it remains impossible to precisely identify the quantitative effects of gelifluction movement at this site. Nevertheless, the results of this monitoring program did provide some empirical evidence of the character of this contribution.

It has already been shown that surface movements measured along the axis of Lobe 10 were, on average, an order of magnitude greater in 1981-1982 than those around the lobe perimeter (Figure 7.7). The accompanying recognition of a concentrated flow of a relatively rapidly moving sediment almost certainly identifies the location where viscous gelifluction dominates over the contributions imparted by seasonal frost heaving. Similar observations of a spatial differentiation in the relative contribution of these two solifluction mechanisms have in fact been recorded by Benedict (1970:220). Assuming that this was indeed the case at Lobe 10 in 1981-1982, it should be possible to infer the relative contribution of both mechanisms by comparing the spatial range of transport values on the lobe surface. Overall, the rate of soil movement along the lobe axis was about 60 percent greater than that around the lobe perimeter where, presumably, gelifluction processes were less active. This was almost certainly the case in 1981-1982, when only minor activity was recorded around the lobe perimeter (Figure 7.7). However, since neither the character of gelifluction flow within this peripheral area, nor the nature of retrograde adjustments were properly evaluated at this site, these conclusions remain

Table 7.8 : Solifluction movement components at Lobe 10 (cm/year).

	total solifluction mov't	-	potential frost creep	=	gelifluction mov't
1980 1981	0.63	-	1.64	=	?
1981 1982	0.72	-	1.24	=	?
1982 1983	0.27	-	1.41	=	?

rather speculative.

7.3.2.2 Lobe 37

Lobe 37 is a large turf-banked solifluction lobe located within the Main Cirque study site in the Mt.Allan area. It is found near the base of a moderate, northwest-facing, slope at 2392 m asl (see Figure 4.9). Composed predominantly of colluvium (Beke, 1969) dominated by sand and silt fractions (see Table 5.6), this lobe contains a small number of weathered stones and blocks which are concentrated around it's perimeter. The tread riser is 30 cm in height, presenting a bulbous profile. It is mantled almost exclusively by mosses (75 percent coverage). Both the parent and tread slope merge imperceptibly above the lobe, where *Salix arctica* and *Dryas octopetala* dominate the plant community. Winter snowfall accumulations usually persist into mid June, with frozen soils at shallow depths common well into the summer months.

Rates of soil movement at this site were measured along a transect which bisected the lobe. In 1980, an inclinometer tube and a dowel pillar column were installed adjacent to one another (0.5 m apart) immediately behind the lobe front at position A (Figure 7.8). At points B (10 m upslope) and point C (20 m upslope) an identical set of instrumentation was installed. In subsequent seasons the tubes were profiled annually (1981-1983), while the pillar column at

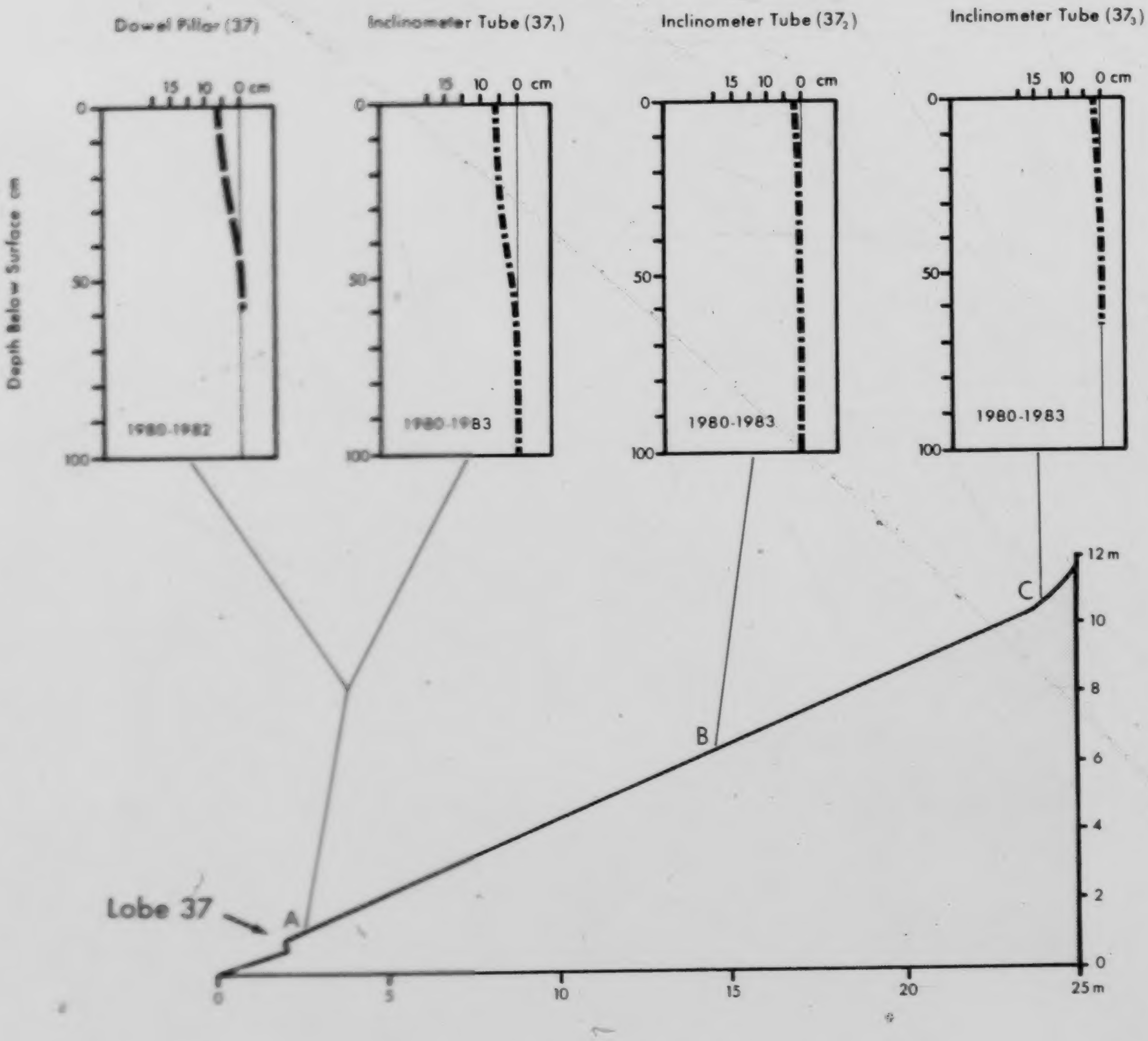

Figure 7.8 : Location and comparison of velocity profiles at the site of Lobe 37, Mt.Allan area.

A was excavated in 1982.

Results

Rates of soil movement were greatest at point A, where they averaged between 2.25 cm/year (Inclinometer Tube 37_1, see Table 6.2) and 2.50 cm/year (Dowel Pillar 37, see Table 6.3) at the ground surface (Figure 7.8). Extending to approximately 0.60 m below the surface, these displacements transported 55.66 cm^3/cm/year of sediment (see Table 6.2). By contrast, only shallow movements involving relatively small amounts of sediment, were observed at the two upslope measurement sites (Figure 7.8). Surface movements at point B averaged 0.53 cm/year over the study period, while at point C they averaged 0.62 cm/year (see Table 6.2).

These observations indicate that significant solifluction on this slope was restricted to the immediate vicinity of the lobe front. This localization of solifluction movement near the slope base has been frequently observed (Rapp, 1960; Rudberg, 1964) and results from a continum of parameters (Carson and Kirkby, 1972:331-335). In this instance, it seems very likely that there was a downslope intensification of solifluction. This is suggested by the convex velocity profiles (see Figures 6.1 and 6.2) at A (c.f. Jahn and Cielinska, 1974:95-96). By contrast the shallow and slower rates of movement measured at points B and C seem to reflect the combined effects of frost creep and normal creep processes (c.f. Selby, 1982).

Evaluation of Movement Mechanisms

If it can be assumed that the magnitude of soil creep due to frost heave at the site of Lobe 37 was similar to that established within the nearby Mt.Rae area [2], then frost creep cannot account for the total annual displacements recorded at point A in the 1980-1981 and 1981-1982 seasons (Table 7.9). This conclusion indicates that gelifluction must have contributed, at a minimum, from 13 to 23 percent of the measured surface movement. However, this contribution was not apparent at point A in 1982-1983, when the total annual

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[2] This is not an unrealistic assumption in the case of Lobe 37, since the geomorphical and climatological setting at this site is very similar to that found at the K2 study site in the Mt.Rae area.

Table 7.9 : Solifluction movement components at Lobe 37 (cm/year).

		total solifluction mov't	-	potential frost creep[1]	=	gelifluction mov't
Point A[2]						
	1980 1981	2.75	-	2.39	=	0.36
	1981 1982	2.00	-	1.54	=	0.46
	1982 1983	1.15	-	2.07	=	?
Point B						
	1980 1981	1.00	-	2.39	=	?
	1981 1982	0.30	-	1.54	=	?
	1982 1983	0.30	-	2.07	=	?
Point C						
	1980 1981	0.70	-	2.00	=	?
	1981 1982	0.85	-	1.29	=	?
	1982 1983	0.30	-	1.73	=	?

1. estimated from the Mt.Rae area observations.
2. inclinometer tube measurements (Tube 37_1).

displacement was much less (45%) than that which could be attributed to the frost creep (Table 7.9). Similarly, at points B and C, the downslope rates of soil were, in every year, exceeded by the potential frost creep.

Two important conclusions emerge from these observations of soil movement at Lobe 37. First, the measurements made at points B and C demonstrate that the actual creep which occurred at these locations was much less than the potential values suggested by the frost heave studies. It is, therefore, reasonable to assume that the contributions from gelifluction can be largely disregarded at these points. This suggests that retrograde movements reduced the potential frost creep calculated for points B and C by from 12 to 85 percent over the study period (Table 7.10). Secondly, if the soil movements obtained at points B and C do approximate the magnitude of frost creep occurring at this plot, they provide an avenue for summarizing the contributions of the major solifluction mechanisms to downslope movements at point A.

The character of retrograde movements at point A were distinguished by assuming they attained magnitudes similar to those established at points B and C. Because total solifluction movement at point A was measured annually with an inclinometer tube (Tube 37_1), these observations could be combined to distinguish the contributions of the different mechanisms involved in solifluction activity on a yearly basis. As Table 7.11 shows, this analysis indicates that frost creep accounted for the smallest percentage of movement at point A, with retrograde displacements of between 0.49 to 1.46 cm/year reducing the potential movements by a minimum of 31 percent. This emphasizes that gelifluction was likely the dominant solifluction mechanism measured at point A, accounting for about 77 percent (1.80 cm/year) of the surface movement.

7.3.2.3 Lobe 50 and Lobe 51

Lobes 50 and 51 are located on a 22°, north-facing slope in the Parkers Ridge study area at 2071 m asl (see Figure 4.17). This slope is festooned with well-vegetated solifluction landforms and Lobes 50/51 are typical examples of the eight individual lobes studied at this site

Table 7.10 : Retrograde movements at Lobe 37, Mt.Allan area (cm/year).

plot[1]	1980-1981			1981-1982			1982-1983		
	PFC[2]	SM[3]	RM[3]	PFC	SM	RM	PFC	SM	RM
B	2.34	1.00	1.34	1.19	0.30	0.89	2.03	0.30	1.73
C	2.00	0.70	1.30	1.02	0.80	0.22	1.74	0.30	1.44
mean (% actual mov't)			1.32 (61%)			0.56 (48%)			1.59 (84%)

1. see Figure 5.6 for locations of points at Lobe 37.
2. PFC = potential frost creep (estimated from Mt.Rae area).
3. SM = total solifluction movements measured.
4. RM = retrograde movements.

Table 7.11 : Solifluction movement components at Lobe 37 (cm/year).

plot years	SM[1]	=	PFC[2]	+	GF[3]	-	RM[4]
1980 1981	2.60	=	2.00	+	1.82	-	1.22
1981 1982	2.25	=	1.02	+	1.72	-	0.49
1982 1983	2.05	=	1.74	+	1.77	-	1.46

1. SM = solifluction movements (Tube 37_1).
2. PFC = potential frost creep.
3. GF = gelifluction flow.
4. RM = retrograde movements.

(see Section 4.4.1.2.). Winter snowpacks linger until mid July, after which they retreat upslope. *Salix arctica* is the most dominant plant within the local vegetation cover, although *Cassiope tetragona* is significant locally.

The tread surfaces of these adjoining lobes have moderate slopes (7° to 11.5°), characterized by irregular patches of bare soil and isolated carapaces of vegetation (see Figure 4.18). Both lobes have steep bulbous risers which average over 50 cm in height. The lobes are composed of a sandy-silt containing some cobbles and stones (see Table 5.6).

Solifluction at this plot was monitored by 7 inclinometer tubes installed in July 1980 (Figure 7.9). Four of the tubes were inserted into the tread surface of Lobe 50 (# 2, 3, 4, 5), while a single tube (# 7) was placed in Lobe 51. Two additional tubes (# 1 and 6) were installed 1.5 m in front of each tread riser. Annual surveys of the tubes were completed in 1982 and 1983.

Results

The results of these annual surveys indicated that there were large variations in the rates and volumes of sediment transported within these two lobes. For instance, on the tread surface of Lobe 50 downslope movements ranged from 0.55 to 1.20 cm/year (Table 7.12). Movements in both lobes decreased rapidly below the surface, although they did indicate virtually all of the deposit was being transported downslope (Table 7.12). However, it did appear that the rate of sediment transport, particularly at Lobe 50, was decreasing as the lobe front was approached. This suggests that these sediments are being stranded behind a slower moving lobe front.

Soil movements in front of the tread riser were slower and confined to shallower layers (between 5 and 13 cm) than those observed within the lobes (Table 7.12). This indicates that Lobes 50/51 are encroaching upon sediment which is moving downslope itself, albeit more slowly.

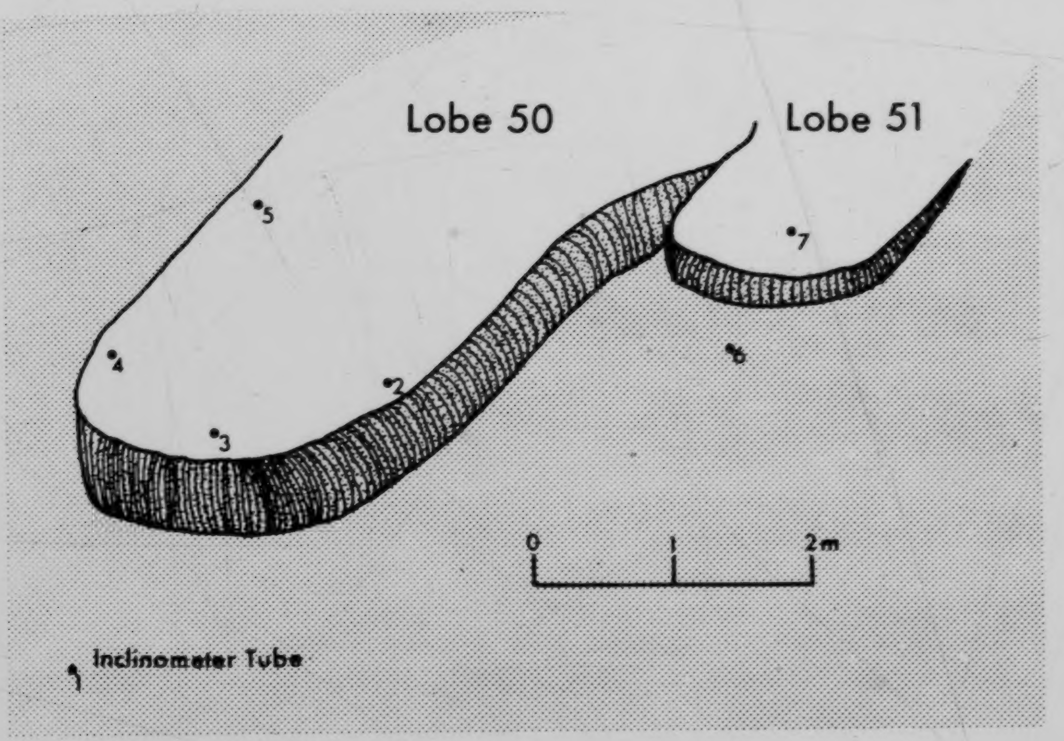
Lobe 50
Lobe 51
5
7
4
2
6
3
0
1
2m
Inclinometer Tube

Figure 7.9 : Schematic illustration of inclinometer tube placement at Lobe 50 and Lobe 51.

Table 7.12 : Solifluction movements at Lobe 50 and Lobe 51, 1981-1983.

Lobe #	tube #	location	surface mov't cm/yr	volumetric mov't cm^3/cm/yr	maximum depth of mov't cm
50	1	slope	0.10	1.60	5.0
	2	tread	0.55	24.08	62.0
	3	tread	0.88	9.82	56.0
	4	tread	0.80	13.41	35.0
	5	tread	1.20	23.49	56.0
51	6	slope	0.45	3.20	13.0
	7	tread	1.30	18.35	55.0

Evaluation of Movement Mechanisms

Soil movements at Lobes 50/51 demonstrate that solifluction was restricted to locations behind the lobe snout. In fact, sediments within the lobes were transported from 3 to 12 times more quickly downslope than those situated below the lobe snouts. If it is assumed that the low rates and magnitudes of displacement measured below the snouts were primarily attributable to frost creep activity, the relative contribution of gelifluction to solifluction on the lobe tread can be estimated.

Comparing the rates of movement between these two lobe settings, on the parent slope and on the lobe tread, suggests that the lobe tread surfaces were transported downslope about 68 percent faster. Given that the average depth of this activity was greater than 50 cm below the ground surface (Table 7.12), it seems that solifluction on the tread surfaces was dominated by contributions from deeply seated gelifluction (c.f. Benedict, 1976). However, since the actual frost creep contribution could not be ascribed at this site, and because retrograde and gelifluction movements occurred simultaneously (c.f. Benedict, 1970:220), the proportional influence of gelifluction at these plots may be considerably more or less than has been indicated.

7.3.3 Discussion

These investigations of the contributions of gelifluction to solifluction within the field area were, necessarily, somewhat conjectural. The approach used allowed only for an empirical evaluation of its local significance at a restricted number of plots. However, the similarity of these observations to more detailed descriptions of gelifluction (c.f. Washburn, 1967; Benedict, 1970; Gamper, 1981) led to three conclusions.

First, these observations confirm that, where gelifluction operates efficiently, it introduces an accelerated form of solifluction. At Lobe 10, gelifluction, at a minimum, resulted in about a 60 percent increase in the average rate of solifluction. Similarly, it was estimated at Lobe 37 that gelifluction was responsible for about a 77 percent increase in the rate of movement and at Lobes 50/51 a 68 percent increase.

Secondly, while the investigations at Lobes 10, 37 and 50/51 assigned considerable local importance to gelifluction, observations at many of the other lobe plots suggest that this contribution may be anomalously high. In fact, much of the solifluction recorded fell within displacement ranges normally attributed to frost creep and normal creep (c.f. Selby, 1982; Saunders and Young, 1983). This suggests that gelifluction is not a significant component of solifluction activity within this area at present.

Finally, a large proportion of the velocity profiles obtained had concave downslope shapes (see Lobe 10, Figure 6.1), usually associated with creep movements (Kirkby, 1967; Benedict, 1970; Jahn, 1979b; Sohma, et. al., 1979). A summary of these results indicates that solifluction was generally slower at the site of concave velocity profiles (Table 7.13), transporting less than 60 percent of the sediment displaced where convex profiles were observed (see Lobe 37_1, Figure 6.2). Assuming that convex profiles represent sites where gelifluction

Table 7.13 : Comparison of solifluction movements by velocity profile.

	CONCAVE DOWNSLOPE			CONVEX DOWNSLOPE		
	n	sm_1	vm_2	n	sm	vm
Mt.Rae	20	0.74	10.07	8	0.68	15.18
Mt.Allan	15	0.96	16.42	3	1.42	30.60
Parkers Ridge	10	0.83	12.50	2	1.00	22.05
FIELD AREA	45	0.84	13.00	13	1.03	22.61

1. sm = surface movements (cm/year).
2. vm = volumetric movements (cm^3/cm/year).

dominated (c.f. Mackay, 1981:1668), suggests that significant gelifluction occurred only at about 22 percent of the measurement sites. To what extent gelifluction was masked by retrograde movements at the other sites remains unknown.

7.4 Conclusions

The investigations discussed in this chapter suggest that frost creep mechanisms are the most predominant component of present-day solifluction. This is emphasized by the velocity profiles which appeared to describe gelifluction dominated movements at less than 22 percent of the sites examined. Further, significant gelifluction was discovered to be spatially limited to seasonally saturated locations near the midpoint of the lobe's axes. On the basis of these observations, it is suggested that where gelifluction dominated it resulted in sediment transport rates, which at a minimum, were an order of magnitude greater than the average rates shown by this study. However, these observations also showed that the contributions of both frost creep and gelifluction to solifluction transport often paled in comparison to the influence of retrograde movements, which were shown to reduce potential transport magnitudes by at least 50 to 70 percent.

8. CONTEMPORARY SOLIFLUCTION ACTIVITY : ENVIRONMENTAL CONTROLS

8.1 Introduction

The rate and character of solifluction is dependent upon, or influenced by, a variety of environmental parameters. In order to gain some insight into the context of these relationships within the Alberta Rocky Mountains field area, investigations were completed to elucidate the impact of several prominent environmental parameters on local solifluction activity. This chapter documents the results of these investigations and comments upon the importance of a number of geomorphological, climatological and biological parameters in defining the rate of contemporary solifluction activity measured within this mountainous setting.

8.2 Geomorphological Controls

The influence of a number of geomorphological parameters on the rates of activity measured by this study was examined through a comparison of their attendant variations. Specifically, the differential inputs of several locational parameters and a number of different sediment properties were analyzed to demonstrate their relationship to the magnitudes of solifluction recorded. Emphasis was placed upon evaluating these relationships through a variety of significance tests (Till, 1974).

8.2.1 Locational Parameters

The influence of site on solifluction had previously been described by Price (1970a, 1973), who demonstrated that a lobe's physical setting contributes significantly to its rate of activity. For this study, three site parameters: altitude; gradient; and aspect; were studied to distinguish their affect on the rates of solifluction within the field area. This information was derived from the site descriptions summarized in Section 5.3 and from the movement studies in Chapter 6.

8.2.1.1 Altitude

The results of correlation analyses indicated that altitude had a significant impact on the rates of solifluction measured by this study (Tables 8.1 and 8.2). Except for surface activity measured within the Mt.Rae area, there was a general trend of reduced solifluction motion with increasing elevation. While this characteristic was probably related to the combined effects of changes in climate and vegetation with height (c.f. Rudberg, 1972; Caine, 1976a; C.Harris, 1982), it can be concluded from the results of this study only that the most active solifluction settings corresponded to locations near the local treeline.

8.2.1.2 Gradient

The effect of gradient on the solifluction movements recorded by this study were examined with reference to several slope functions. The sine function was described since Washburn (1967:95) had previously shown it to have a direct impact on solifluction rates, although C.Harris (1981a:122-123) was unable to distinguish any such relationship. The sine-squared function figured extensively in similar discussions of soil creep (Kirkby, 1964; Schumm, 1964; Owens, 1969), while the tangent function was included to evaluate the likely significance of frost creep (Davison, 1889; Washburn, 1967).

It was evident from the results of a series of correlation analyses of the different expressions of slope angle and the measured rates of solifluction, that only surface transport rates were affected by slope gradients (Table 8.1). Volumetric movements apparently bear little relationship to surface slopes (Table 8.2). This is somewhat perplexing in view of the strong linear relationship described between these two movement descriptors (see Table 6.3 and Figure 6.5), and suggests these conclusions need further qualification. Of the different functions, overall, sine-squares were the least significant.

Figure 8.1 depicts the relationship between surface movements and the sine of the slope gradient. Based on the linear relationship described ($y = 1.73x + 0.17$, $r = 0.370$, where $r^{.05} = 0.250$), it appears that solifluction is unlikely to be effective on slopes much lower than 5° in the field area. However, it is also obvious from Figure 8.1 that there is considerable scatter

Table 8.1 : Correlation coefficients: surface movements (cm/year) vs locational factors.

Mov't vs	Mt.Rae	Mt.Allan	Parkers Ridge	FIELD AREA
Altitude (m asl)	0.065	-0.441	-0.538	-0.308_1
Parent Slope Gradient				
θ	0.418_1	0.387	0.157	0.367_1
sin θ	0.417_1	0.388	0.166	0.379_1
$\sin^2$ θ	0.425_1	0.377	0.117	0.242
tan θ	0.419_1	0.384	0.138	0.360_1

1. significance 95%.

Table 8.2 : Correlation coefficients: volumetric movement ($cm^3/cm/year$) vs locational factors.

Mov't vs	Mt.Rae	Mt.Allan	Parkers Ridge	FIELD AREA
Altitude (m asl)	-0.279	-0.292	-0.498	-0.333_1
Parent Slope Gradient				
θ	-0.075	0.287	0.010	0.108
sin θ	-0.082	0.286	0.019	0.111
$\sin^2$ θ	-0.079	0.273	-0.056	0.069
tan θ	-0.075	0.294	-0.084	0.107

1. significance 95%.

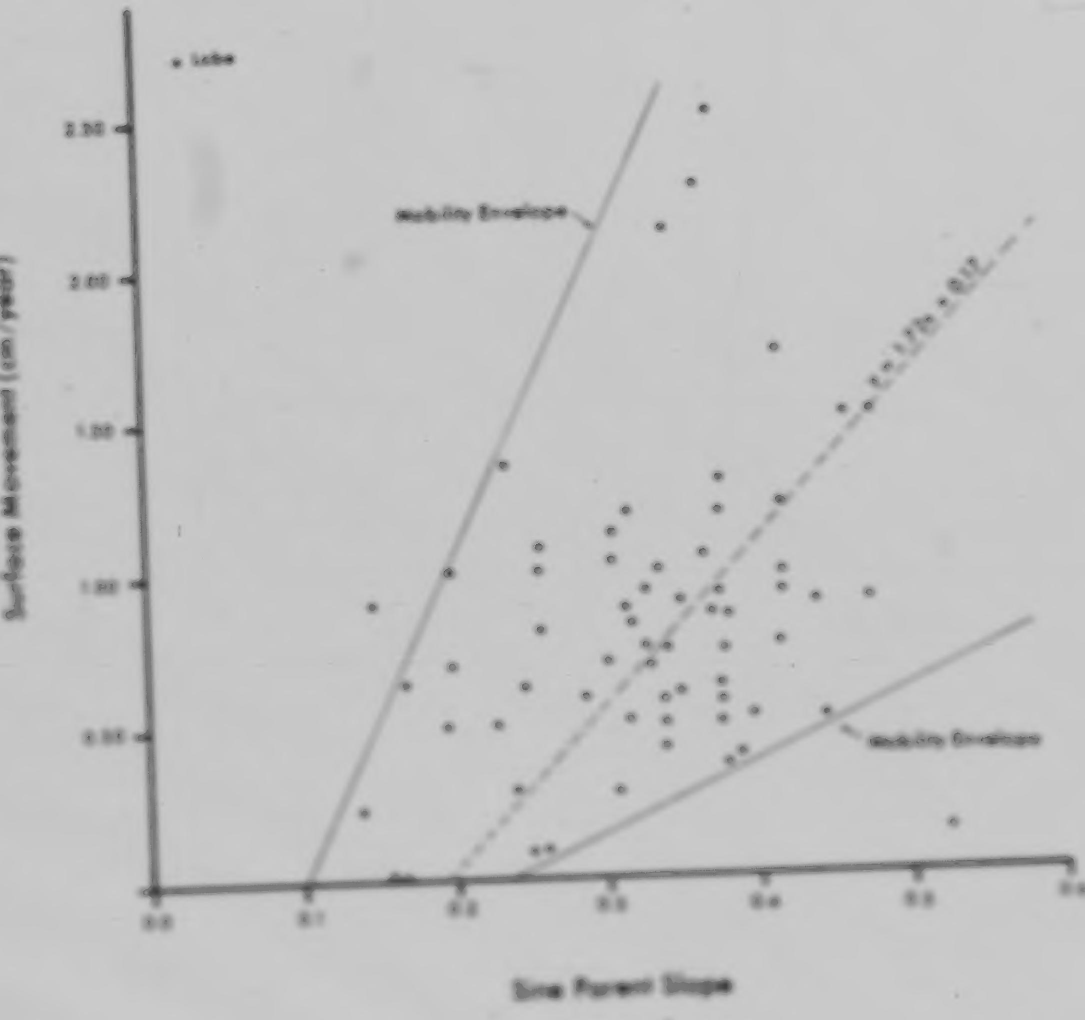

Figure 8.1 : Relationship between surface movement rates and slope gradient.

around the mean (r² = 14%). Thus, it seems best to enclose the data within a mobility envelope. This envelope indicates that local variations imparted by other independent variables are introducing considerable ambiguity into this relationship. Besides the sine function, surface movements were shown to be proportional to the slope tangent (Table 8.1). However, similar to the sine expression, only about 13 percent (r²) of the accompanying variance was attributable to this function. Taken together these results demonstrate that solifluction is affected by surface slope. However, in view of the extremely large variances which appear (approximately 86%), it would be wrong to assume slope gradient is a primary determinant of local solifluction.

8.2.1.3 Aspect

Aspect appears to be an important control of solifluction within this area. This is demonstrated in Figures 8.2 and 8.3 where the average rate of surface and volumetric movements measured are plotted in 10° azimuth classes. Both rate functions indicated significantly higher rates of movement occurred at plots with north to east aspects, where surface movements took place almost twice as fast as on slopes with southerly to westerly aspects.

This pattern of movement is most likely related to delayed seasonal thawing, resulting from topographic shading (c.f. Benedict, 1970) and/or excessive snowpack accumulations on these north- to east-facing slopes due to the prevailing winds (c.f. C.Harris, 1982). Presumably, this situation results in an increase in the number of short-lived saturated gelifluction events on these slopes, as late-season thawing/melting of soil/snow releases excessive meltwater. This conclusion supports the observations made by Price (1970a:165; 1973:240) and C.Harris (1982:38), who believe such slopes will be wetter and thus subject to more rapid solifluction.

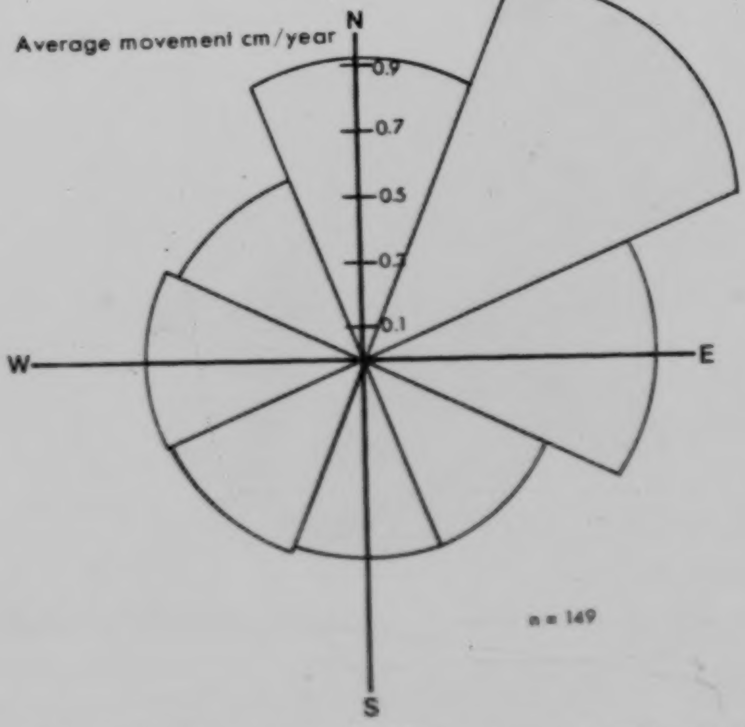

Figure 8.2 : Variation of annual surface movements with aspect.

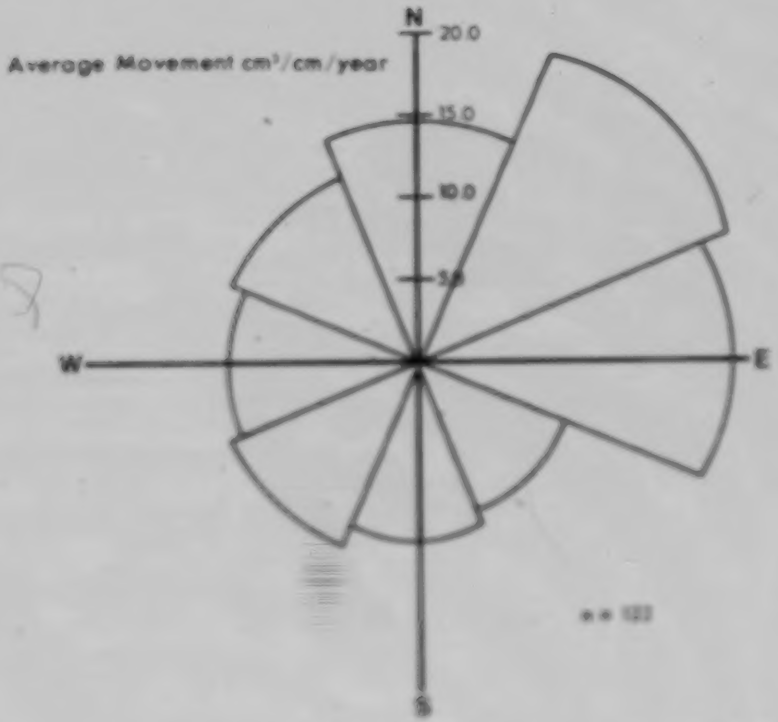

Figure 8.3 : Variation of annual volumetric movements with aspect.

8.2.1.4 Summary

The foregoing observations demonstrate that the physical setting of solifluction lobes within the field area did influence the rates of solifluction measured by this study. Specifically, they indicated that the most rapid rates of solifluction occurred on moderately sloping, northeast-facing sites, in close proximity to the local treeline.

8.2.2 Sediment Properties

The solifluction sediments examined share many physical attributes. This was noted previously in Section 5.4, where it was shown that many of these physical properties do not vary significantly from one study area to the next. For this analysis, three geotechnical parameters: soil texture; unit weight; and index limits; were compared to the measured surface and volumetric movement (Table 8.3).

Table 8.3 : Correlation coefficients: soil movements vs soil characteristics.

	SURFACE MOVEMENTS			VOLUMETRIC MOVEMENTS		
	n	r	signif.	n	r	signif.
PARTICLE SIZE (< 2.00 mm)						
Sand (%)	36	0.062	NS[1]	35	-0.107	NS
Silt (%)	36	-0.142	NS	35	0.070	NS
Clay (%)	36	-0.085	NS	35	-0.033	NS
Silt + Clay (%)	36	-0.139	NS	35	0.057	NS
BULK DENSITY (kN/m^3)						
Unit Weight	15	0.052	NS	15	0.398	NS
CONSISTENCY LIMITS						
Liquid Limit	35	-0.300	NS	34	-0.308	NS
Plastic Limit	30	-0.289	87%	28	-0.267	80%

1. NS = not significant

8.2.2.1 Soil Texture

Soil texture had little discernible impact on the measured rates of solifluction. While several textural parameters were examined to indicate their relationship to solifluction, no significant correlations surfaced (Table 8.3). In fact, as shown by Figures 8.4 and 8.5, any effect textural variations had on the rate of solifluction were, almost certainly, obscured by other factors (c.f. Benedict, 1970:212).

8.2.2.2 Unit Weight

In much the same manner that textural variations give little indication of affecting the rate of solifluction so, too did variations in unit weight values appear to have almost no impact on the measured displacements. No significant correlations were apparent (Table 8.3), although given the small sample size (n=15), it may well be that any effects were simply overshadowed by more dominant parameters.

8.2.2.3 Index Limits

The importance of consistency limits to solifluction is summarized in Table 8.3. These analyses suggested that there was no correlation between the rates of soil movement and the attendant liquid limits. In contrast, it appeared that an increase in a sediment's plastic limit did result in some reduction of surface and subsurface transport rates. Essentially, these analyses demonstrated that as soil's cohesiveness increased, it was accompanied by a general reduction in the rate of solifluction transport.

8.2.2.4 Summary

These analyses indicated that variations in the sedimentological properties of these solifluction soils were not responsible for any of the observed solifluction rate variations. However, since no significant spatial variations in these properties were detected within the field area (see Section 5.4), this was not a surprising conclusion.

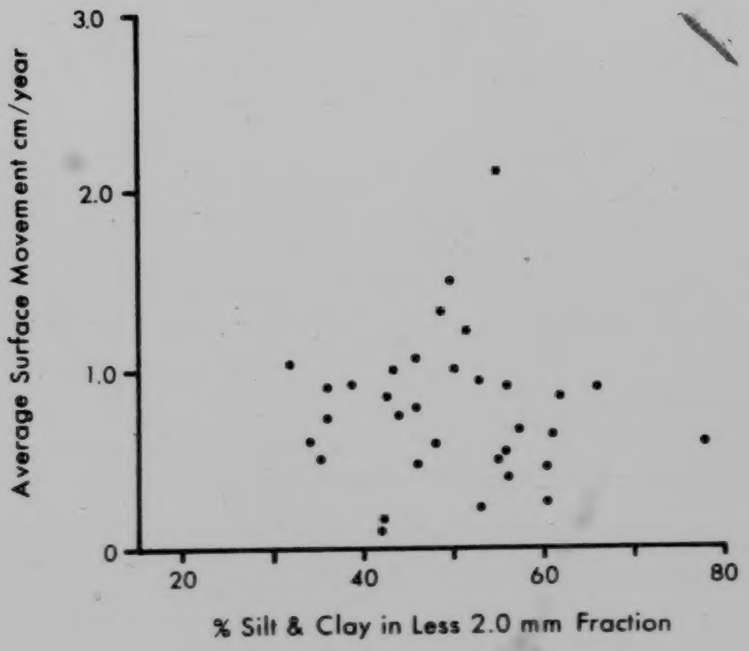

Figure 8.4 : Relationship between soil texture and rate of surface movement.

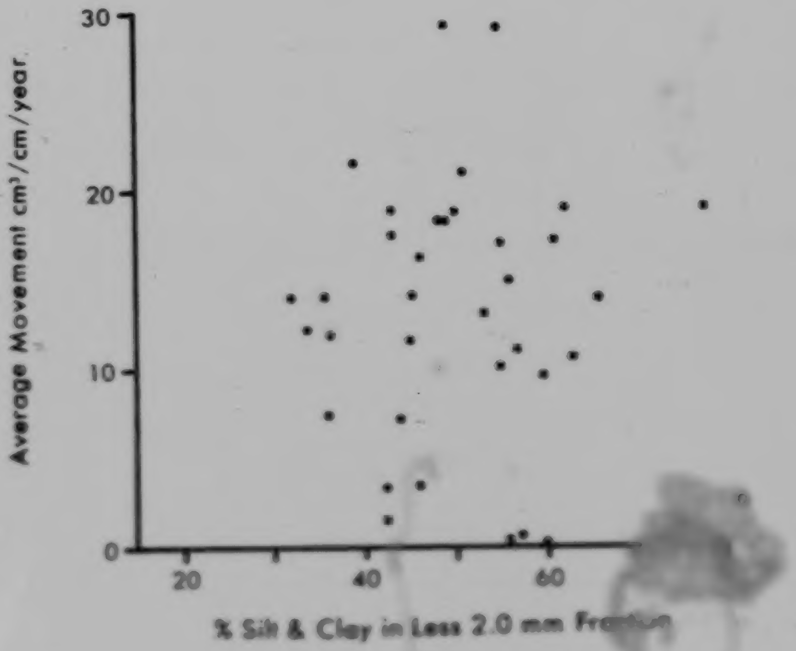

Figure 8.5 : Relationship between soil texture and volumetric rate of movement.

8.3 Climatological Controls

In mountainous terrain the climate experienced by an individual solifluction lobe is dependent upon the local mesoclimate and surface conditions. Thus, while the environmental character of a solifluction site is defined by the regional climate, local microclimates as affected by differences in topography (c.f. Barry and Van Wie, 1974), vegetation (c.f. Price, 1971a), and the patterns of snow accumulation and melt (c.f. C.Harris, 1974), play a large part in determining the behavior of solifluction (c.f. Washburn, 1967; Rudberg,1974). The aim of this section is to illustrate the importance of these climatic relationships to solifluction within the field area over the study period.

The nature of these climatic relationships was assessed in two ways. First of all, an attempt was made to characterize the seasonal climatic rhythms within the three study areas over the research period. The purpose of this is to illustrate regional climatic variations which might have differentially affected solifluction. Secondly, a series of microclimatic investigations were completed within the Mt.Rae area to illustrate the relationships between microclimatologic patterns and localized solifluction activity.

8.3.1 Climatic Character of the Study Areas

The climatic data available for the three study areas are very limited and, in many instances, fragmentary (c.f. Lester, 1974; Janz and Storr, 1977). Long-term records from representative alpine tundra sites are simply not available. Because of this restriction the data used to characterize the climate of each study area was taken from the nearest high altitude stations. Two of these, at Highwood Summit in the Mt.Rae area (see Figure 4.4) and at Parkers Ridge (see Figure 3.16), are valley floor sites. However, their position immediately below an inverted treeline almost certainly provides data representative of that within the alpine zone. The third site, at Twin One in the Mt.Allan area (see Figure 4.12), is located within an open subalpine forest in close proximity to the local treeline.

8.3.1.1 Air Temperature

Seasonal air temperatures within the three study areas corresponded closely during the study period (Table 8.4). Winter temperature extremes illustrated the largest amplitude, whereas summer temperatures showed much less variation. Mean annual temperature differences between the three sites were generally less than 0.5° C.

Annual air temperatures over the study period corresponded closely to the long-term norms reported previously (see Chapter Five). Comparison of air temperatures at the three study sites indicated slightly above average conditions occurred over the winter of 1980-1981, while below average temperatures occurred in both 1981-1982 and 1982-1983 (Table 8.4). Variations in summer air temperature were less clearly defined, but appeared normal.

8.3.1.2 Precipitation

The seasonality of precipitation differed only slightly among the three study areas (Table 8.4). At all three sites the snowcover lasted at least from November to the end of June. However, while most of this snow fell in December to February at Parkers Ridge, a majority of the winter snowfall is received in April at the two Front Range sites (Janz, 1976, Storr and Golding, 1976). Consequently, extensive areas of bare ground persisted within the alpine throughout most of the winter period due to redistribution by wind and evaporation by chinooks (c.f. Fisera, 1977). At all three sites most of the snow melted during June-July.

The lowest precipitation at all three sites occurred during the summer period, although singular rainstorm events were not uncommon in any of the areas. Generally, the amounts of summer precipitation (May to October) received within the Mt.Rae and Mt.Allan areas were quite similar, while precipitation totals at Parkers Ridge were slightly greater.

The monthly precipitation totals indicated considerable variability over the record period (Table 8.4). While September, 1980, and July, 1981, were particularly wet throughout the Rockies, precipitation in the last half of 1980 and during the winter of 1980-1981 remained well below normal in the Mt.Rae and Mt.Allan areas. During the same period, greater than average values were recorded at Parkers Ridge. A similar trend was apparent in the following

Table 8.4 : Monthly climatic parameters from the three study areas.

	MT. RAE[1]		MT. ALLAN[2]		PARKERS RIDGE[3]	
month	temp. (° C)[4]	precip. (mm)[5]	temp. (° C)[6]	precip. (mm)[5]	temp. (° C)[7]	precip. (mm)[7]
1980						
July		84.0	10.0	89.7		
August		53.0	6.0	68.2		
September		112.0	4.7	151.2		
October		25.0	2.3	17.4	0.9	38.4
November	-8.2	89.0	-4.7		-6.1	115.0
December	-11.1	102.0	-8.0		-11.2	144.0
1981						
January	-5.4				-5.7	7.0
February	-11.3	43.0		43.0	-8.0	112.5
March	-4.9	30.5		40.0	-5.4	40.0
April				50.0	-2.7	99.0
May				24.0		
June					5.4	39.5
July		121.0		121.0	8.6	104.2
August		53.0			11.7	33.8
September		28.0			6.0	28.9
October		45.0			-1.1	51.2
November		23.0		30.0	-4.6	24.5
December	-9.9	53.0		48.8	-12.3	112.0
1982						
January	-12.3				-14.9	76.0
February	-12.0				-11.2	166.0
March	-6.5				-7.9	64.0
April	-4.0				-4.4	54.0
May					15.0	25.0
June						
July						
August						
September						
October					-0.3	35.0
November					-9.5	33.0
December					-10.3	73.0
January	-13.5					
February	-11.6					
March	-10.8					

1. Highwood Summit (2230 m asl).
2. Twin One (2380 m asl
3. Lower Parkers Ridge (267 m asl).
4. mean air temperature, Alberta Parks and Recreation, 1980-1982.
5. total precipitation, Environment Canada, 1969-1981.
6. mean air temperature, Environment Canada, 1980-1982.
7. mean air temperature and total precipitation, Environment Canada, 1978-1982.

summer and, to some extent, winter.

Winter snow accumulation provided an empirical measure of the seasonal tempo of snow release. Below normal snowpacks accumulated at the two Front Range sites in 1980-1981 and again in 1982-1983, when similar conditions prevailed at Parkers Ridge. These conditions proved to be the precursor of early snow melt at solifluction sites in all three areas. In other years, with closer to average snowpack accumulations (1981-1982 in the Mt.Rae area, 1980-1981 and 1981-1982 at Parkers Ridge), snow release dates at the various solifluction sites were extended.

8.3.1.3 Climate Summary

The climates described by the parameters of air temperature and precipitation are unequivocally periglacial in character (c.f. Karte and Liedtke, 1981). Unfortunately, however, the paucity of data recorded over the period of this study precluded any detailed analysis of how these climatological parameters varied among the three study sites. As a result, the influence that subtle mesoclimatic shifts had on solifluction was not adequately assessed. In summary, though, because preceding discussions indicated that solifluction movements throughout the field area were similar from year to year (see Section 6.3), it seems likely that slight fluctuations in areal climates detected over the study period were not sufficient to engender dramatic changes in the rates of solifluction. This is not to say, however, that the consequent microclimatic changes did not affect the patterns and manner of solifluction displacement.

8.3.2 Microclimatological Studies

The relationship between microclimate patterns and localized solifluction behavior provides considerable insight into the operation of solifluction processes (c.f. Price, 1970a; C.Harris, 1974; Kaiser, 1980). In order to assess the role microclimate plays in the morphodynamic behavior of solifluction within the field area, several of the study lobes within the Mt.Rae area were intensively monitored over the study period. The results of this instrumentation program and the likely impact microclimate had on solifluction described at these lobe sites are discussed in the following sections.

8.3.2.1 Methodology

Microclimatological data from four main stations and one temporary station were collected from within the Mt.Rae area in the 1980-1983 period. Four of these stations, Tombstone Valley (2380 m asl); Ptarmigan Ridge (2385 m asl), Highwood Ridge (2430 m asl), and K2 (2520 m asl), were installed at high altitude locations where parallel investigations of solifluction were underway (see Figure 4.4 for locations of the climate stations). Established in either 1980 or 1981, these stations were dismantled following the completion of the study program in 1983. The final station included within this analysis was the permanent valley bottom Highwood Summit meteorological station (2208 m asl), which was used to evaluate winter conditions in this area.

Two of the stations, Highwood Ridge and K2 (see Figure 4.4), were equipped with screened Lambrecht thermographs and recording Belfort rain gauges. Two sets of SoilTest fiberglass soil moisture-temperature cells (one at 5, 25, 50 cm depths in Lobe 15 and one at 5, 25, 50, 75 cm depths at Bedstead A) were installed at Highwood Ridge to monitor soil climates. At the K2 study site four moisture-temperature sets (three at 5, 25, 50 cm depths in Lobes 11, 12, 13; one at 5, 25, 50, 75 cm depths at Bedstead B) and a Lambrecht 3-Point Distance Thermograph (at 5 25, 50 cm depth in Lobe 10) were used to evaluate environmental changes below the surface (see Figure 4.9 for site locations).

The station at Ptarmigan Ridge (see Figure 4.4) was equipped with a Weathermeasure hygrothermograph and a Taylor Maximum-Minimum Thermometer located in a Stevenson screen 1 m above the ground surface. Soil climates were monitored with a Lambrecht 3-Point Distance Thermograph (at 5, 25, 50 cm depths in Lobe 34) and a set of moisture-temperature cells (at 5, 12, 25, 50, 75, 110 cm depths in Lobe 35).

In 1980 a temporary station in Tombstone Valley was equipped with a Lambrecht Thermograph and a Taylor Maximum-Minimum Thermometer, located within an instrument screen placed on the ground, and an unshielded Sacramento rain gauge.

These climatic stations were visited weekly during the spring, summer and early fall to provide a continuous record of air temperatures. Daily precipitation summaries from the permanent Highwood Summit station were supplemented in the summer months by raingauge data from Highwood Ridge and K2. This provided a more exact measure of local rainstorm effects. The soil climate data obtained with the moisture-temperature cells were collected at periodic intervals, usually weekly during the summer months. A YSI insertion probe, gravimetric soil samples and laboratory procedures outlined by SoilTest (1975) were used to obtain site calibrations for each of the moisture-temperature cells.

8.3.2.2 Air Temperature

Air temperature differences between stations in the Mt.Rae area illustrated several things. For instance, average monthly temperatures at the K2 site were consistently cooler than those recorded at the other two high altitude stations (Table 8.5). These differences were particularly acute in the fall freeze-up periods when diurnal air temperatures at K2 only rarely rose above 0.0° C. Across the valley, air temperatures at Ptarmigan Ridge, during the same period, attained values amongst the warmest recorded in the local alpine zone. In fact, air temperatures at this site were consistently warmer, by 3.0° C or more, than air temperatures at the nearby but more exposed Highwood Ridge site. While this trend corresponds to an average summer lapse rate over the record period of approximately 5.5° C per 100 m within the local alpine zone, it undoubtedly reflects differences in the local net radiation budgets resulting from variations in the aspects of the sites. The correspondingly cooler minimum monthly temperatures recorded at Highwood Summit emphasize the significance of cold air drainage down local alpine slopes (D.Smith, 1979:67).

In much the same manner, diurnal temperature ranges were observed to vary seasonally between the different stations. Daily temperature ranges were greatest at Ptarmigan Ridge where radiation warming is particularly effective. Conditions were less extreme at the other two high altitude stations. During the spring to fall seasons, differences between the daily maximum

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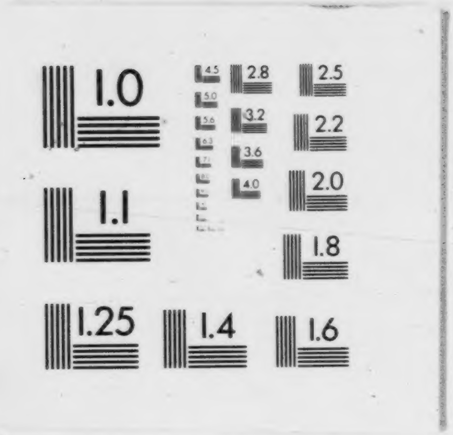

1.0
4.5
5.0
5.6
6.3
7.1
2.8
3.2
3.6
4.0
2.5
2.2
2.0
1.1
1.8
1.25
1.4
1.6

Table 8.5 : Mean monthly air temperature (°C) at stations in the Mt.Rae area.

month	Highwood Summit[1] 2208 m asl	Tombstone Valley 2380 m asl	Ptarmigan Ridge 2385 m asl	Highwood Ridge 2430 m asl	K2 2520 m asl
1980					
July		7.3[2]		7.9[2]	10.4[2]
August		5.4		4.6	4.9
September		3.8[2]		1.7	0.5
October				-0.2	-2.1
November	-8.2			-6.2	
December	-11.1				
1981					
January	-5.4				
February	-11.3				
March	-4.9				
April					
May					
June				0.6[2]	
July			9.3	5.5	4.8
August			14.5	10.4	9.9
September			7.1	3.1	2.9
October			-3.5	-1.4	-4.3
November			-5.5	-2.7	-5.4
December	-9.9		-8.7[2]	-12.4	
1982					
January	-12.7			-15.1[2]	
February	-12.0				
March	-6.5				
April	-4.0				
May					
June			7.9[2]	7.1	9.6[2]
July			7.9	6.6	5.7[2]
August			8.0	7.0	6.8[2]
September			5.6	4.2	
October			5.2[2]	-4.6[2]	
November				-9.3	

1. unpublished data, Alberta Parks and Recreation.
2. incomplete monthly record.

temperatures recorded at each of the stations frequently exceeded 6.0° C. On the other hand, daily minimum temperatures rarely differed by more than 3.0° C. Temperature differences during the winter period were generally insignificant.

These broad differences in air temperature regimes at each of the stations emphasize the variability of local frost climates (Table 8.6). For instance, while air temperatures fell below 0.0° C in almost every month of the year above the treeline, there appeared to be considerable spatial differences in the characteristics of these frost climates. During the summer months (June-August), when frost-alteration days averaged less than 6 per month, frost-free periods were common at all elevations. By September, cooler air lowered mean diurnal temperatures and increased the number of frost-alteration days experienced at the higher altitude stations. However, by mid October rapid ambient cooling at the K2 site acted to reduce the total number of frost cycles when compared to those at the Highwood Ridge site. Freezing temperatures in late October to early November signalled the end of the diurnal frost-alteration periods at both of these sites. Air temperature oscillations at the Ptarmigan Ridge site prolonged the frost-alteration period there until at least late November. However, by early December frigid air temperatures embraced all of the sites within the Mt.Rae area and no further frost cycles were recorded until the following melt season.

8.3.2.3 Precipitation

While there were slight variations in the amounts of precipitation received by each of the microclimatic stations, these were not accurately assessed by the present study. In fact, monitoring of rainfall totals (July-September) at Highwood Ridge and K2 detected only insignificant differences in 1980 and 1981. Clearly though, the same cannot be said of winter snow accumulations which illustrated marked redistribution in the local alpine.

Snow Depths and Duration

Snow began to accumulate at these stations by mid October, although significant snow depths were unusual prior to early December. Total winter accumulations varied from site to

Table 8.6 : Frost climates in the Mt.Rae area, 1980-1983.

	PTARMIGAN RIDGE			HIGHWOOD RIDGE			K2		
month	ID[1]	FF[2]	FA[3]	ID	FF	FA	ID	FF	FA
1980									
Jul				0	19	2[4]	0	15	2[4]
Aug				0	15	16	0	20	9[4]
Sep				2	6	22	7	6	17
Oct				12	5	14	17	3	11
Nov				27	0	2	20	0	3[4]
1981									
Jun				3	4	9[4]			
Jul	0	29	2	0	20	11	0	19	12
Aug	0	31	0	0	29	2	0	29	2
Sep	2	19	9	6	13	11	11	5	15
Oct	7	3	21	15	0	16	19	0	12
Nov	14	4	12	19	1	10	24	0	6
Dec	31	0	0	31	0	0			
1982									
Jun				0	26	4	0	13	0[4]
Jul	0	26	5	0	26	5	0	27	4
Aug	0	28	3	0	27	4	0	20	2[4]
Sep	2	22	6	4	18	8			
Oct	0	2	7[4]	10	16	5			
Nov				31	0	0			

1. ID = ice days, daily temperature below 0.0° C.
2. FF = frost-free days, daily temperature above 0.0° C.
3. FA = frost-alteration days, days with both freezing and thawing temperatures.
4. incomplete monthly data.

site, with maximum snowpacks ranging from 1.5 to 2.5 m. Similarly, snow release dates varied both spatially and temporally, although most sites were free of snow by early July. An exception was the K2 site, where the snow release date tended to be delayed until mid July.

Summer Precipitation

Rainstorms can have both direct (Herz, 1964; Stromquist, 1983) and indirect (Fritze, 1971) effects on solifluction. For this reason the 141 storms recorded at the Highwood Ridge station (1980-1982) were assessed, using the methodology presented by Caine (1976b), to determine their character. These observations suggested that rainstorms were more frequent in July and August (mean of 17.5 events) than September (mean 10 events), but that September storms generally involved greater amounts of precipitation (mean 40 mm) falling with greater intensity (mean 1.72 mm hr^{-1}). This late summer skewing of maximum precipitation values was likely an important source of near-surface soil moisture during the fall freeze-up period.

8.3.2.4 Soil Climates

The cadence of soil climate regimes is very important to the solifluction process. For example, seasonal variations in the thermal condition of the ground directly effect the physical behavior and strength of a soil (Farouki, 1981; Czurda,1983). During the fall freeze-up thermodynamically driven phase movements create situations where moisture migration generates frost heaving (Konrad, 1980; Konrad and Morgenstern, 1980), critically altering soil structures (Booth, 1981; Mermut and Arnaud, 1981). Soil stability in the following melt period is dependent upon this activity, as well as the character of on-going phase changes (McRoberts, 1973). Knowledge of the temporal positioning and magnitude of seasonal variations in soil temperature and moisture is thus clearly important to understanding the characteristics of local solifluction processes.

Soil Temperatures

Previous investigations of alpine soil temperatures in the Mt.Rae area had succeeded in establishing the basic structure of the local subsurface thermal regimes (c.f. Baig, 1972;

Trottier, 1972). Subsequent observations of sporadic permafrost bodies at high elevation within the same area (D.Smith, 1979) served to illustrate the significance of microclimate to local thermal regimes.

Records of mean monthly soil temperatures (1980-1982) gathered for this study illustrated substantial inter- and intra-site variation (Table 8.7), which were to some extent due to such intrinsic site factors as plant cover, exposure and slope (c.f. Carson and Moses, 1963).

a)Fall temperatures

Soil temperatures showed a rapid decline at all stations in the autumn period (September-November) following the return of cooler ambient air temperatures. While warmer ground persisted at depth until relatively late in the season, soil freezing tended to be initiated prior to snowpack accumulation. In most cases, the freezing plane had advanced beyond the 50 cm depth mark by mid November. Near-surface temperature gradients during this period often showed marked diurnal oscillations in response to extremely wide daily air temperature fluctuations.

Figure 8.6 provides a temporal image of air and soil temperature changes at the K2 study site. Cool air temperatures in the autumn of 1980 initiated an early period of shallow freezing, which persisted at some of the lobes throughout the fall period. In the following year, rapid air temperature declines in early October inaugurated the seasonal frost front at a much later date. The average rate of frost penetration to the 50 cm mark was 0.9 cm/day in 1980 and 1.8 cm/day in 1981.

Thermal conditions in the ground at Ptarmigan Ridge for the autumn periods of 1980, 1981, 1982 are illustrated in Figure 8.7. In contrast to the situation at K2, sub-zero temperatures were not initiated at this site until late in the fall season. For example, freezing temperatures at 5 cm were not detected until mid October in both 1980 and 1982. This dilatory characteristic is believed to result primarily from the site's protected southwest exposure. This acted to delay freezing of the ground, and ultimately resulted in an extremely rapid rate of frost penetration later in the season. In 1980 the frost front advanced at an average rate of 2.3

Table 8.7 : Average monthly soil temperature (°C) data, Mt.Rae area (1980-1982).

Lobe	Depth	Month								
#	(cm)	J	J	A	S	O	N	D	max	min
K2										
10_1	5		-1.7	4.3	0.7	-2.5	-3.0		7.6	-3.3
	25		-0.5	2.9	2.0	-0.5	-3.0		5.2	-1.3
	50		0.2	2.7	2.4	0.0	0.0			-1.0
11_2	5	2.2	4.6	6.2	3.5	-0.3			13.0	-1.5
	25	0.0	3.3	5.5	4.0	0.9			8.0	0.0
	50	0.0	2.3	4.0	3.7	1.3			6.0	0.0
12_2	5	3.5	5.5	9.2	4.9	0.4			20.0	-2.5
	25	0.6	3.2	8.0	5.7	1.3			10.0	0.0
	50	0.5	3.1	7.2	5.8	1.9			8.5	0.0
13_2	5	2.1	5.2	6.2	2.9	-0.7			11.5	-3.0
	25	0.0	3.4	5.4	3.4	0.8			8.0	0.0
	50	0.0	2.6	4.4	3.0	0.8			6.0	0.0
Highwood Ridge										
15_2	5	4.3	4.8	7.2	3.9	1.2			9.3	-3.0
	25	2.7	4.1	6.2	3.6	1.6			8.0	-3.0
	50	2.2	3.5	5.1	3.4	1.8			6.0	-1.0
Ptarmigan Ridge										
34_1	5	1.9	7.5	8.2	5.4	0.3	-2.1	-9.0	21.5	-11.0
	25	0.9	4.7	7.1	5.5	0.8	-1.7	-6.8	12.4	-8.0
	50	-2.2	0.3	3.3	3.8	1.9	0.4	-2.5	9.0	-3.0
35_2	5	6.2	11.2	11.0	10.3	2.3	-1.3	-2.5	24.0	-4.0
	12	3.6	9.8	9.6	6.6	3.0	-0.5	-2.0	12.8	-3.0
	25	2.9	9.5	9.2	7.4	4.3	0.7	-0.5	12.0	-2.0
	50	1.0	7.1	8.4	7.1	4.4	1.7	0.0	10.0	-0.5
	75	1.2	5.9	7.8	7.7	4.7	2.3	1.0	9.0	0.0
	110	1.1	4.3	4.3	7.6	4.8	2.8	2.0	7.8	0.0

1. continuous soil temperatures recorded with a Lambrecht 3-Point Distance Thermograph.
2. day-time spot temperatures recorded at periodic intervals with a SoilTest Moisture-Temperature Meter.

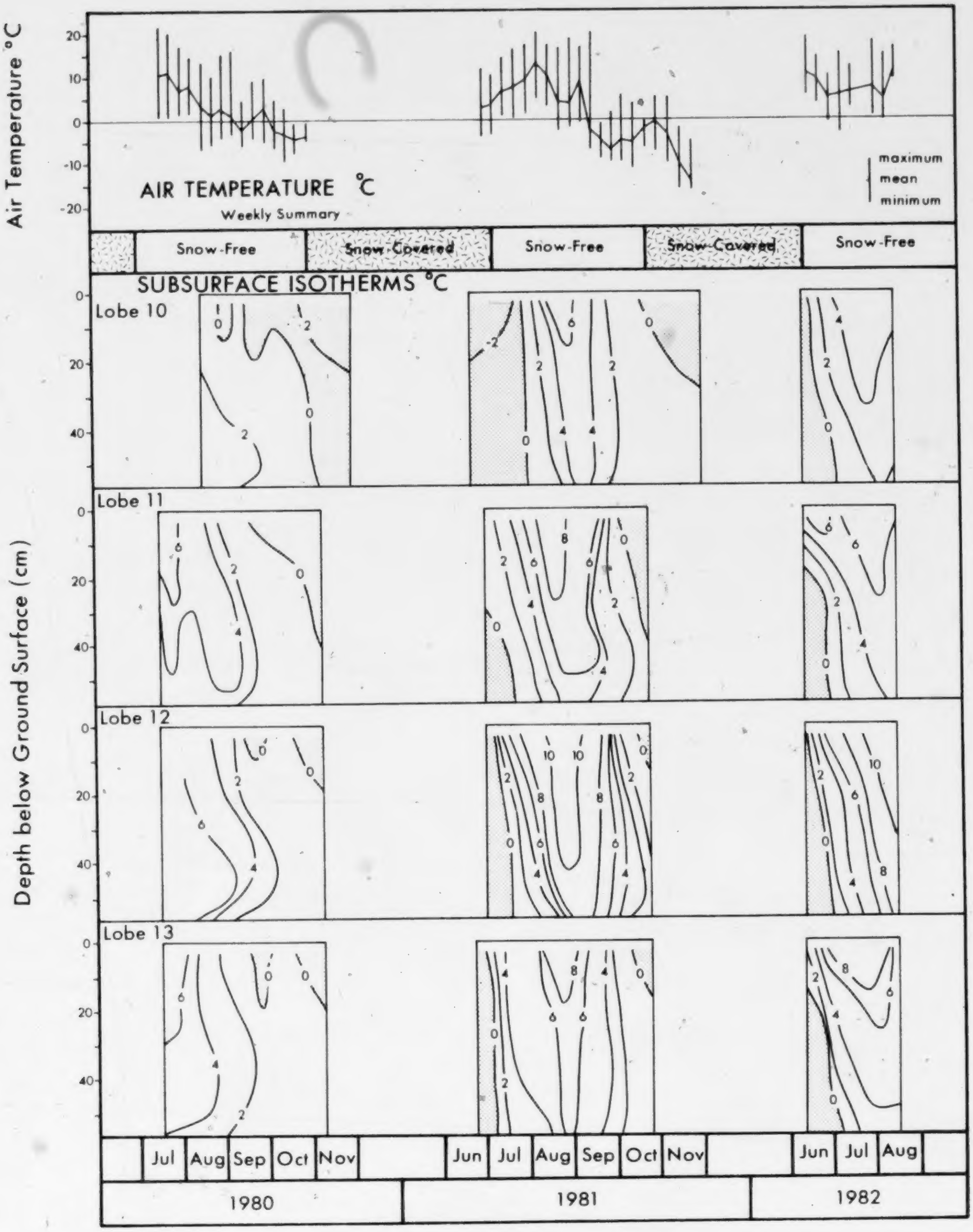


Figure 8.6 : Air temperature and subsurface thermal regimes at the K2 study site.

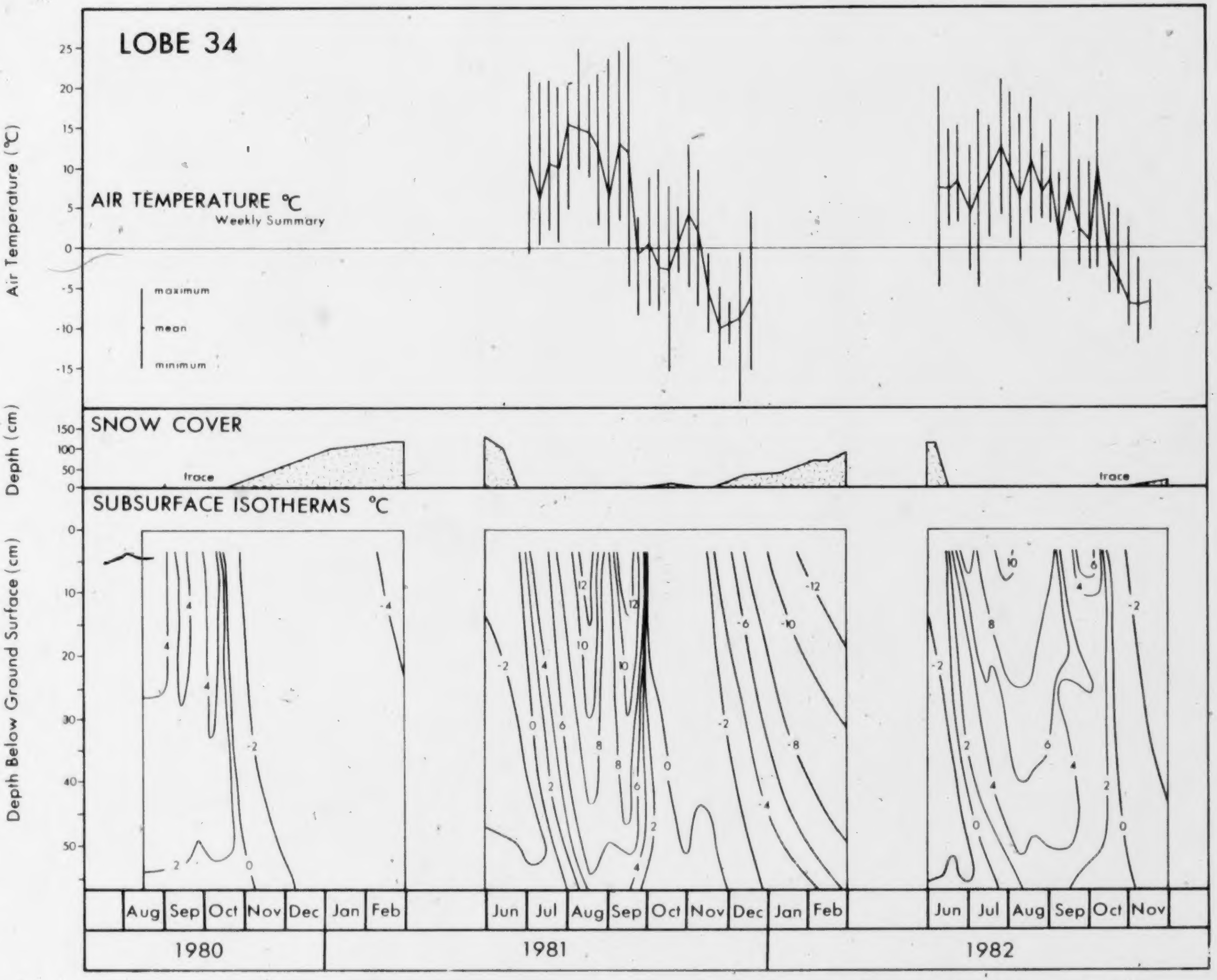


Figure 8.7 : Air temperature and subsurface thermal regime at Lobe 34, Ptarmigan Ridge.

cm/day, while in 1982 it progressed downwards some 5.6 cm/day.

b)Winter temperatures

Fragmentary records indicate the lowest monthly soil temperatures at all depths occurred over the winter period (November-June), with the most extreme values noted in January, February or March. During the early winter, variable snow depths had a marked effect on the severity of soil freezing. This is illustrated at Lobe 34 when the first half of the 1980-1981 and 1981-1982 seasons are compared (Figure 8.7). Thermal conditions in 1980, when near normal accumulations of snow mantled the site, are noteworthy by their limited range. In the following winter, an unusually shallow snowpack persisted well into the season. This provided the ground with insufficient insulation from sub-zero air temperatures and a succession of cold waves penetrated deeply into the soil.

Soil temperatures in the late-winter period are poorly represented in the data base. However, there appeared to be a gradual moderation of ground temperatures as air temperatures gradually rose and late-season snow storms insulated the ground (Figure 8.7).

c)Spring temperatures

The character of soil temperatures in the spring season (June-July) was dependent upon the timing of snowpack ablation. Because deep accumulations of snow commonly persisted into these summer months, local mean air temperatures were usually well above 0.0° C prior to the initiation of soil thawing (Figure 8.6). As a consequence, local ground temperatures were often isothermal prior to advance of the thaw plane. In some instances, short-term reverse temperature gradients appeared as near-surface soil gradually acclimatized to overlying isothermal snowpacks (Figure 8.7).

Soil thawing began relatively early at Ptarmigan Ridge, where the snowpack commonly melted by late June. Initially thawing progressed at a rapid rate (mean 5.9 cm/day) but with deeper penetration slowed considerably (mean 1.8 cm/day). At the K2 site, where the snowpack usually remained until late July, the thaw plane advanced at an average of 1.9

cm/day, at least until the 50 cm depth.

During the spring season, short-lived freezing cycles acted to slow the downward advance of the thaw plane. However, since the effects of these cycles were only rarely observed to penetrate deeper than 5 cm, their impact on solifluction was likely minimal.

d)Summer temperatures

Soil temperatures recorded over the summer period (July-September) varied considerably from site to site (Figures 8.6 and 8.7). The highest monthly soil temperatures occurred in August, with only the deepest probes indicating a September maximum (Table 8.7). An exception to this pattern was caused by an unusually long period of warm dry September weather in 1981. This initiated a second phase of soil warming, particularly at the Ptarmigan Ridge site where the maximum temperatures recorded at all depths occurred during that period. At all stations soil temperatures abruptly decreased in the late-summer period as cooler air invaded the alpine in advance of the fall period.

e)Discussion

Several important aspects of solifluction soil thermal regimes are revealed by these investigations. First, they illustrate the great environmental differences which exist even within small areas of the local alpine. For instance, the thermal variations documented at the K2 site, particularly during the summer months, clearly showed the important role slope exposure and vegetation cover had in defining local temperature regimes. At the west-facing Lobe 12 more direct solar radiation caused markedly warmer soil temperatures. Differences between Lobes 10 and 13 resulted primarily because of the thick insulating cover of turf at the former plot.

A second noteworthy aspect of these alpine soil temperatures is their marked temporal variability. Thermal regimes in both summer and winter periods were shown to have significant year to year variations, although for very different reasons. Annual differences in winter soil temperatures were attributed to winter snow depth variations; while summer soil temperature differences resulted mainly from seasonal air temperature variations. In the case of winter soil temperatures, more extreme values were recorded when thin to non-existent snowpacks allowed cold air to penetrate deeply into the soil. Conversely, a rapidly established deep seasonal snowcover acted to insulate the underlying soil from cold winter air temperatures. As a whole, summer soil temperatures responded quickly to changes in air temperature. Thus, seasons when the average air temperature was relatively cool corresponded to seasons of low thermal extremes below the ground surface (Figure 8.7).

Finally, these measurements point out the speed with which both thaw and frost fronts travel through these solifluction soils. Since the character of each of these thermal periods is important to solifluction (Washburn, 1967; Benedict, 1970), this apparent confinement to relatively narrow time-frames has significant repercussions. For instance, rapid advance of the frost front significantly reduced the potential for frost creep by limiting the time available for moisture migration to the freezing plane (c.f. Penner, 1972; Fahey, 1979). In contrast, rapid melting of the ground increased the potential for slope instability during the thaw period because it increased the potential for gelifluction flow (c.f McRoberts and Morgenstern, 1974; McRoberts, 1978).

Soil Moisture

Soil moisture plays a decisive role in the solifluction process (c.f. Washburn, 1967; Chambers, 1970). Previous investigations of soil moisture in this (Baig, 1972; Trottier, 1972), and nearby areas (Harlan, 1969; S. Harris, 1972; Richards, 1981), had already indicated that substantial variations were common within this alpine zone. However, up until the time of this study there had been little appraisal of the spatial characteristics of these fluctuations, specifically as they related to solifluction landforms.

The cells used to monitor soil moisture were utilized in a number of similar investigations (Price, 1970a; Fahey, 1974). Measuring the electrical conductivity of the soil (SoilTest, 1975), they provide an estimate of soil water ratios (Hillel, 1971; Schmugge, et. al., 1981). Weekly measurements of the cells began in August, 1980, after a two-week stabilization period. Moisture observations were discontinued each fall, once it was established the soil was frozen.

Table 8.8 presents a monthly summary of these soil moisture investigations. Moisture values were observed to decrease over the summer period as higher temperatures gradually dried the soil. During the early fall period, noteworthy precipitation events caused temporary increases in soil wetness above seasonal norms. Readings taken in the period immediately after the thaw plane advanced through the soil were higher than those encountered prior to freeze-up. This seems to indicate substantial soil water contributions resulting from the melting of snow.

Table 8.8 : Mean monthly soil moisture (%) in upper 50 cm of solifluction soil, Mt.Rae area.

	LOBE #				
month	11	12	13	15	35
1980					
August	33	nd[1]	24	32	nd
September	31	31	24	38	nd
October	22	29	24	37	nd
1981					
July	29	30	33	38	nd
August	32	25	31	31	21
September	30	22	23	25	15
October	25	21	18	26	19
1982					
June	22	36	29	38	26
July	33	27	29	38	22
August	31	25	22	30	20
September	nd	nd	nd	nd	22

1. nd = no data

The character of soil moisture storage varied at each of the lobe sites. The high soil water contents documented at Lobe 15, for example, were a consequence of the high clay content of the sediment. The seasonally low values at Lobe 35 reflected the effects of intense radiation drying. Conditions at Lobes 11, 12, and 13, located at the K2 study site (see Figure 4.9 for locations), were more comparable (Figure 8.8). The striking feature at these sites were the short-lived periods of high soil moisture which accompanied thawing of the ground and the general decrease in soil moisture over the summer period. Of particular interest were irregularities observed in the latter trend. For example, near-surface moisture content increased in an uncharacteristic manner in September, 1980, almost certainly due to the persistent snow showers observed over that period.

Discussion

The spatial and temporal patterns of soil moisture revealed by these investigations suggests that soil water is an important contributor to the character of local solifluction. These investigations indicated that soil water decreased to seasonal lows immediately prior to annual freezing of the soil (c.f Mackay,1980). Although this trend did vary annually and appeared responsive to specific climatic events, the general dryness of these sediments substantially reduced their potential for significant frost heaving (c.f. Fahey, 1971, 1974). Interestingly, these observations suggest that the high soil moisture values noted early in the thaw period resulted primarily from infiltrating moisture derived from melting snowpacks (c.f. Kane, 1980).

The second consequence of these seasonal fluctuations in soil moisture are the attendant changes of soil state or consistency. It is well established that the behavior and strength of a sediment subject to solifluction is dependent upon its water content (c.f. Hutchinson, 1974; C. Harris, 1977). The character of this relationship can be estimated by documenting seasonal variations in the potential states of consistency. To elucidate these values the Liquidity Index (LI) for each moisture measurement was calculated using:

$$\mathrm{LI} = Wn - PL / PI$$

where Wn is the water content of the soil, PL the plastic limit of the soil and PI its plasticity index (Bowles, 1979:35-36). Sediment in a potentially liquid state has a value greater than 1.0, whereas in a plastic state it has a value between 1.0 and a value less than 0.0 indicates the soil is

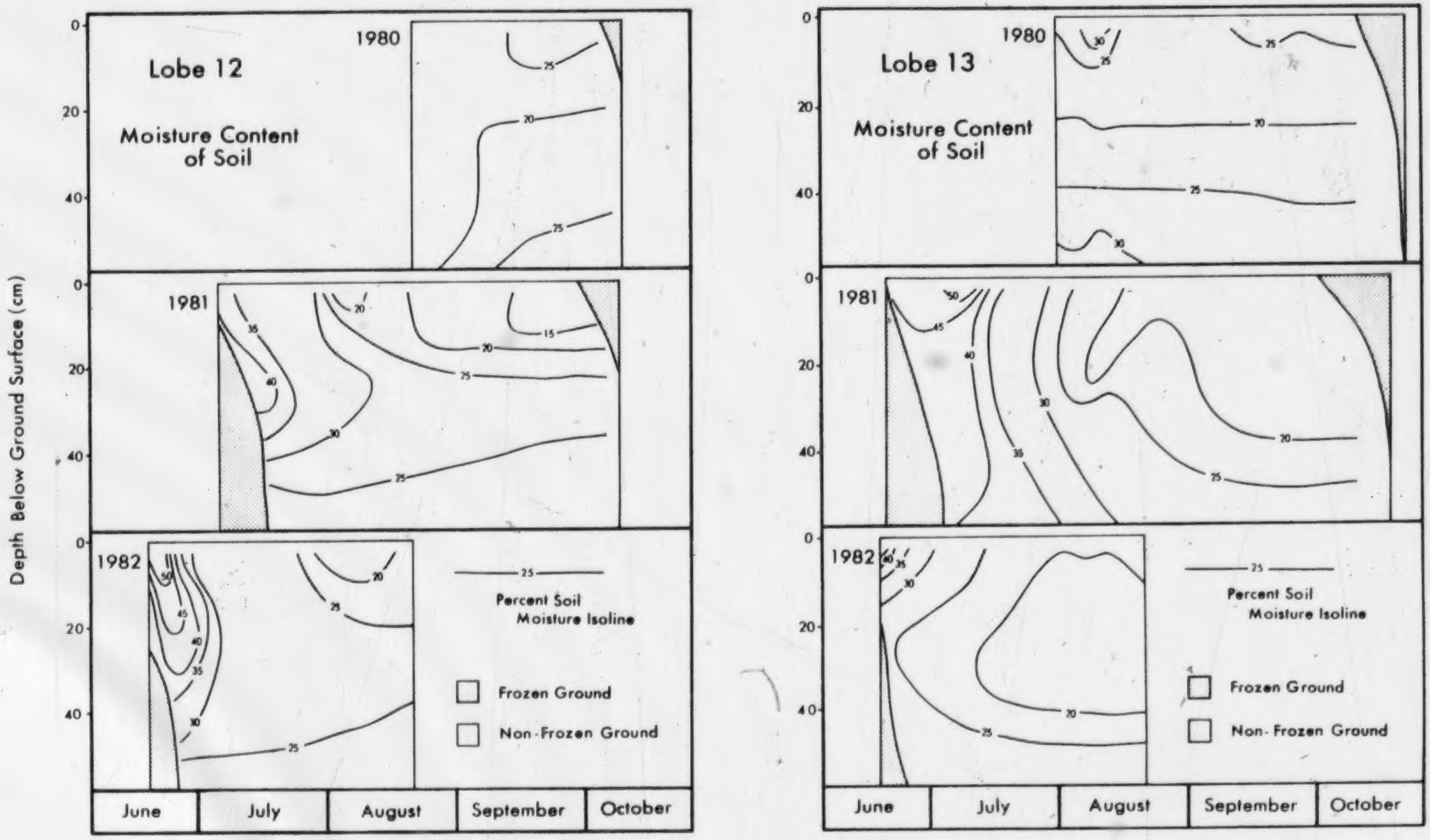


Figure 8.8 : Soil moisture conditions at Lobe 12 and Lobe 13, 1980-1982.

non-plastic.

Liquidity values in this study were shown to vary both annually and seasonally. Table 8.9 provides a monthly comparison of the liquidity indexes established for each surveyed lobe. These calculations emphasized the temporal independence of annual state transitions and demonstrated that there was an increase in soil cohesiveness over the summer months following a potentially unstable post-melt period. During most years this involved a transition from a potentially liquid to a non-plastic state. However, this did not appear to be the case at Lobe 15 where soil water contents remained high throughout the unfrozen period. Presumably, this condition resulted from melt of the sporadic body of permafrost situated upslope (c.f. D.Smith, 1979). In contrast Lobe 35 barely attained a plastic state.

Table 8.9 : Mean monthly liquidity index[1] in upper 50 cm of solifluction soil.

	LOBE #				
month	11	12	13	15	35
1980					
August	0.7	nd[2]	0.0	3.2	nd
September	0.3	1.4	0.0	4.1	nd
October	-1.4	1.0	0.0	4.0	nd
1981					
July	0.1	1.3	0.9	4.1	nd
August	0.6	0.0	0.7	3.0	0.2
September	0.3	-0.6	-0.1	1.9	-1.0
October	-0.9	-0.9	-0.6	2.1	-0.3
1982					
June	-1.4	2.8	0.5	4.2	0.2
July	0.7	0.5	0.5	4.2	-0.6
August	0.3	0.0	-0.2	2.9	-1.0
September	nd	nd	nd	nd	0.7

1. liquidity index values: <0.0 = non-plastic; 0.0-1.0 = plastic; >1.0 = potentially liquid.
2. nd = no data.

Close examination of the seasonal LI trend at Lobes 12 and 13 is more revealing. At both lobes, seasonal thawing of the ground prompted tangential decreases of potential consistency as soil water contents rose sharply. At Lobe 12, in both 1981 and 1982, near-surface sediments remained in a state of potential liquidity for only a short time (Figure 8.9). At Lobe 13 conditions in 1981 contrasted sharply with those noted in 1982 (Figure 8.9). During the summer of 1981 the sediment contained within the lobe remained in a potential state of liquidity for almost a month. In the following year, this potentially liquid state was limited in duration and confined to the uppermost layers of sediment.

8.3.2.5 Microclimate and Solifluction

The microclimatological observations made within the Mt.Rae area indicate that soil climates at the solifluction sites exhibit considerable spatial and temporal variability. The temporal variations in soil temperature and moisture are felt to be significant enough to have influenced the local rates of solifluction. In order to evaluate the influence of these microenvironmental fluctuations on solifluction activity, they are compared to movement data collected concurrently at the K2 study site.

The characteristics of the K2 study site were reviewed previously (see Section 4.2.1.3). Despite its relative inacessibility, it was possible during the summer months of 1980, 1981 and 1982 to describe the microclimate of this site in relatively good detail. This was particularly true of the soil climates at Lobes 10, 11, 12 and 13 (see Figure 4.9 for locations). The data obtained from these investigations was discussed in the preceding section. In conjunction with the solifluction data obtained at the K2 site (see Tables 6.2, 6.3 and 6.4) and the measurement of frost heave recorded at Bedstead B (see Figure 7.3), a good basis is established for discussing the general relationship between microclimate and the character of solifluction transport at this site.

Preceding discussions indicate that microclimatological variations were commonplace at the K2 study site during the research period. Specifically, they demonstrate that under warm and very dry summers, such as occurred in 1981 (Tables 8.5 and 8.6), soil moisture within the

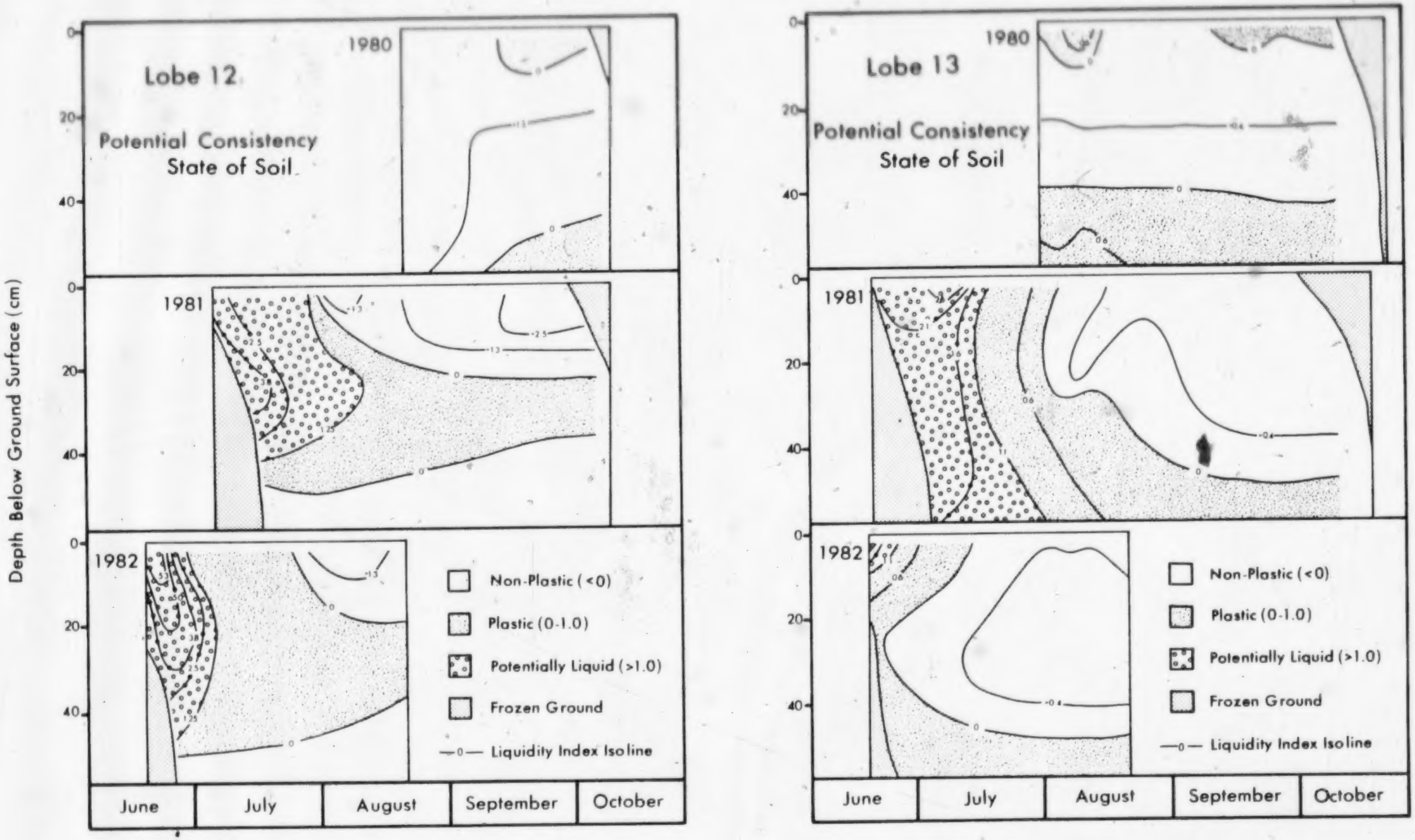


Figure 8.9 : Potential consistency states of soil at Lobe 12 and Lobe 13. 1980-1982.

near-surface sediments of the ridge summit was markedly depleted (Table 8.8). In 1981, when this situation occurred immediately prior to an extremely abrupt freeze of these soils, it substantially reduced the potential frost creep (Table 8.10) by limiting the amount of frost heaving (see Figure 7.3). In fact, the magnitude of potential frost creep at the K2 site was reduced in 1981-1982 by about 24 percent over that estimated for the preceding season (Table 8.10). This situation is reflected in an apparent reduction of about 19 percent in the average rate of surface movement measured in 1981-1982 (mean 0.57 cm/year, CV=64%) compared to that monitored in the preceding 1980-1981 season (mean 0.70 cm/year, CV=37%)(Table 8.11). However, because the snow-release dates differed between the two seasons (Section 8.3.1.2), as did the amount of soil water present in the two thaw seasons (Table 8.8, Figure 8.8), the contributions imparted by gelifluction presumably would have varied as well. In summary, while the microclimatic investigations completed at the K2 study site suggest that soil climate variations influenced the rates of solifluction observed, their specific role could not be deciphered due to the complexity of the attendant interrelationships.

8.3.2.6 Microclimate Summary

A number of points emerge from these analyses. First, monitoring of these characteristics over the research period indicate that there are great variations in microclimate from lobe to lobe. This is not unexpected, given the wide differences in the environmental settings at each of the study lobes. However, because no significant variations in the rates of solifluction were detected within the Mt.Rae area (see Section 6.3), this observation leaves open the question as to the magnitude of climatic change necessary to significantly alter the present rates of solifluction transport measured by this study. Secondly, there appears to be a significant relationship between soil moisture and frost creep. This varied to the point where excessive soil drying reduced heaving and, thereby, retarded the magnitude of subsequent frost creep. Finally, the depth of solifluction, and in particular the contribution derived from gelifluction, was limited to the upper horizons of sediment where seasonal saturation accompanied thawing of the ground.

Table 8.10 : Potential Frost Creep (cm/year), K2 study site.

Lobe #	θ	1980 1981	1981 1982	1982 1983
10	20.0	1.64	1.24	1.41
11	18.0	1.46	1.11	1.27
12	22.5	1.86	1.41	1.62
13	18.0	1.46	1.11	1.27
14	15.0	1.21	0.91	1.67
21	8.0	0.63	0.58	0.55
41	15.5	1.25	0.94	1.08
mean		1.36	1.04	1.18

Table 8.11 : Surface movements (cm/year), K2 study site.

Lobe #	1980 1981	1981 1982	1982 1983	mean	CV[1]
10	0.63	0.72	0.27	0.54	44
11	0.49	0.39	0.25	0.38	31
12	0.70	0.50	1.00	0.73	34
13	1.10	1.14	0.49	0.88	39
14	1.03	0.89	1.30	1.07	19
21	0.36	0.25	0.09	0.23	59
41		0.10	0.10	0.10	00
mean	0.70	0.57	0.50		
CV	39	64	94		

1. CV = coefficient of variability.

8.4 Biological Controls

The symbiotic relationship between solifluction and vegetation is well established (c.f. Seidenfaden, 1931; Raup, 1969). However, the exact nature of this relationship has been difficult to define. For example, according to many researchers the character of a vegetation cover is directly attributable to the degree of solifluction activity (Hogbom, 1914; Sørensen, 1935; Hanson, 1950; Dahl, 1956; Carbiener, 1966). Conversely, many other researchers suggest that it is the vegetation cover which controls solifluction motion, by retaining water and binding the soil (Frodin, 1918; Sigafoos and Hopkins, 1952; Warren-Wilson, 1952; Washburn, 1967; Price, 1973; Gamper, 1983).

The aim of the research discussed within this section was to provide a basis for discussing this relationship in the context of the field area. Specifically, it was anticipated that a knowledge of the vegetation cover of active lobes, its species composition and relation to specific landforms, would aid in disclosing the characteristics of this relationship and, thereby, provide a relative index of the rate of solifluction activity within the field area. To that end several botanical parameters, including coverage, species tolerance and community composition were documented in order to demonstrate the character of these relationships.

8.4.1 Previous Studies

Although environmental factors are recognized as major determinants of alpine plant community structures (Billings, 1979; Baker, 1983), in frost-affected soils community composition is considered to be strongly influenced by physical disturbance (Jonasson and Skold, 1983; Heilbronn and Walton, 1984b). Solifluction provides a good example of a particular form of recurrent physical disturbance (c.f. White, 1979). While previous documentation demonstrated that solifluction can initiate and maintain broad shifts in species composition and dominance (Warren-Wilson, 1952; Dahl, 1956; Carbiener, 1966; Agnew and Hedberg, 1969), few attempts have been made to relate these botanical observations to corresponding measurements of solifluction activity.

One exception is the work completed by Raup (1969) at Mesters Vig, Northeast Greenland. Utilizing solifluction movement data collected concurrently by Washburn (1967), Raup was able to demonstrate two important points about the relation between solifluction and vegetation. First of all, he discovered that vegetation cover was not a particularly good indicator of solifluction activity at Mesters Vig, since the most rapid rates of solifluction usually occurred at the better-vegetated sites. Raup (1969:137-139) noted that soil moisture was paramount to both, acting to jointly accentuate their mutual prominence. More significantly, Raup (1969:199-201) discovered that certain types of plants were more compatible with solifluction than others.

This research attempted to ascertain whether or not these relationships existed within the field area. This was done by relating the botanical characteristics of cover, tolerance and community composition to the rates of solifluction measured at the study lobes.

8.4.2 Methods

Vegetative fieldwork was undertaken in the July to August period of 1981 and in August of 1982. In the first season voucher collections of vascular taxa were made at a number of representative lobe sites within the three areas. In 1982 more detailed investigations were carried out using three quadrats set out along linear transects situated on the lobe axis (Figure 8.10). Two of the quadrats, Zone A and C (1 x 1 m), abutted the lobe riser. A third, Zone B, spatially linked the other two quadrats but necessarily had less rigidly defined dimensions. Instead, this quadrat had a constant width (1 m) and a second dimension dependent upon the individual riser heights.

Within each quadrat species lists were compiled and community regimes empirically evaluated. Visual cover estimates were made to indicate the relative abundance (Kershaw, 1973:15) of vascular plants, bryophytes, lichen and non-plant material. These estimates were later scaled using a modified Braun-Blanquet classification scheme (Table 8.12).

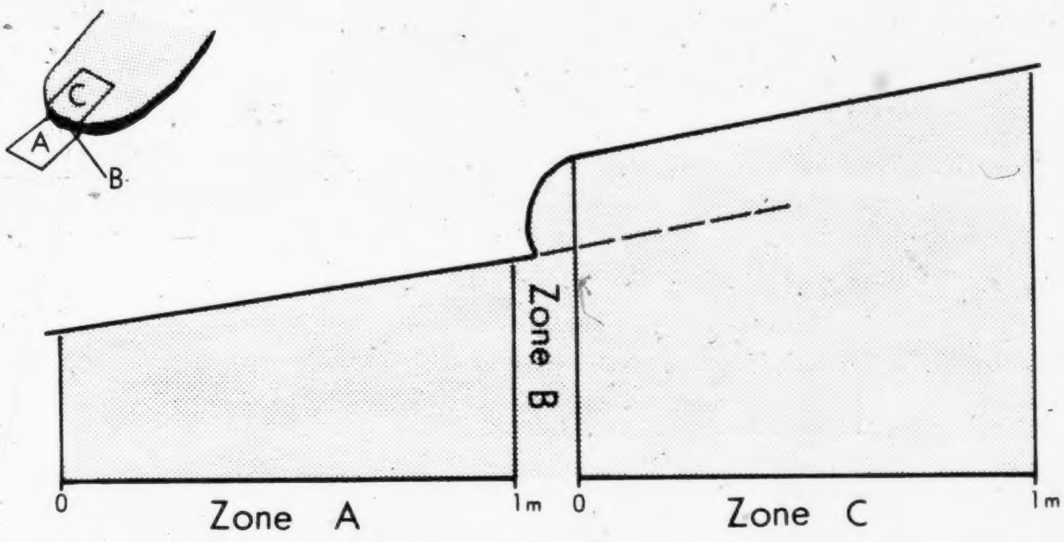

C
A
B
Zone B
0
Zone A
1m
0
Zone C
1m

Figure 8.10 : Transect quadrant zonation used for vegetation inventory.

Table 8.12 : Modified Braun-Blanquet cover classification scale.

Cover Class	Coverage Range(%)
6	76-100
5	51-75
4	26-40
3	16-25
2	6-15
1	1-5
+	less 1
•	present

8.4.3 Analysis

Vascular plants observed in the field and contained in the voucher collection were identified by Dr. M. Sauchyn, University of Saskatchewan. Confirmation of *Erigeron* ssp. was by Dr. J.C. Semple, Department of Botany, University of Waterloo. Nomenclature follows Scroggen (1978-1979), with modifications contained in Moss (1983).

To allow for comparison between the three study areas a similarity index was constructed. This index compares species diversity between sites through similarity coefficients. The procedure used was that of Sørensen which states that the:

$$\text{Index of Similarity (IS)} = 2c \times 100/a + b$$

where a represents the total number of species at site x, b is the total number of species at site y, and c is the number of species common to both (Mueller-Dombois and Ellenberg, 1974:214).

After assessment of the IS index the vegetation data were subdivided, with further analysis restricted to the data from the Mt.Rae and Mt.Allan areas. To elucidate the prominent species associated with each quadrat zone a Prominence Value (PV) was calculated using:

$$PV = C/F$$

where C represents the percentage mean cover and F the quadrat frequency (Stringer and LaRoi, 1970). Further analysis, using a modifiction of the Bray-Curtis method of two-dimensional ordination (Mueller-Dombois and Ellenberg, 1974:277-286) was completed to provide a two-dimensional spatial pattern of species composition. This procedure allowed for later assessment of the exogenic controls of species composition (c.f. Scott, 1974).

8.4.4 Observations

Eighteen solifluction lobes (31 percent of the study population) were sampled to determine their vascular plant composition. This included both general observations and 42 quadrat inventories (36 in the Mt.Rae area and 6 in the Mt.Allan area). In total 83 species of vascular flora in 24 families were identified (see Appendix IV for a complete species list). This included 74 species from the Mt.Rae area, 32 from the Mt.Allan area, and 20 from the Parkers Ridge area.

8.4.4.1 Flora

Using the species lists compiled for each lobe, the floristic similarity between the 18 sites was described. A similarity matrix suggests that only a moderate correlation exists (mean IS = 34.4%) between lobes described from within the three study areas (Table 8.13). However, partial similarity matrices indicate this coefficient is heavily weighted by marked dissimilarity within the Parkers Ridge data (Table 8.14). Correlations describing only the Mt. Rae and Mt.Allan associations are almost identical, both within and between the various lobes. This would seem to indicate the presence of an endemic flora that is common to lobes in both areas.

Mt.Rae Area

Solifluction lobe sites in the Mt. Rae area are mantled by vegetation mats which illustrated remarkable similarity (mean IS = 44.8%), despite their widespread and diverse physical settings. *Salix* ssp.(*S. arctica, S. reticulata*) and other dwarf shrubs (*Dryas octopetala, Vaccinium scorparium*) dominate the vegetation cover of the majority of lobe front and tread surfaces (see Appendix V). At drier and more protected locations (eg. Lobes 4, 12, 28, 34, 35), forbs (*Antennaria lanata, Arnica mollis, Astralagus alpinus, Potentialla diversifolia*) and gramminoids (*Carex nigricans, Juncus drummondii, Kobresia myosuroides*) increase their degree of dominance (Appendix). Riser vegetation varied considerably, depending to a large extent upon local site characteristics. At locations where there was abundant available soil moisture (eg. Lobes 13, 14), mosses and forbs (*Antennaria lanata, Oxyria digyma*) were amongst the most dominant species.

Mt.Allan Area

In the Mt.Allan area the flora found associated with solifluction lobes appear to be typical of that within the local alpine (c.f. Kirby and Ogilvie, 1969; Carroll, 1978). Lobe fronts and tread surfaces are dominated by low shrubs (*Salix arctica, S. reticulata, Dryas octopetala*),

Table 8.13 : Similarity matrix (IS %) for solifluction lobe vegetation.

	LOBE #																	
#	1	3	4	10	12	13	14	22	25	28	34	35	37	38	49	50	57	58
1																		
3	36																	
4	42	33																
10	52	32	44															
12	53	30	47	47														
13	61	31	44	90	65													
14	48	21	35	76	58	67												
22	50	53	49	44	42	44	25											
25	68	47	52	52	42	44	35	49										
28	40	25	65	38	55	46	42	63	37									
34	47	24	36	33	63	45	41	46	36	50								
35	46	18	22	20	52	44	38	38	32	35	74							
37	50	17	45	60	39	55	56	36	49	26	34	22						
38	50	30	49	53	48	62	56	46	57	39	38	27	87					
49	21	21	19	23	21	25	22	23	19	21	00	00	14	18				
50	11	12	21	18	23	16	16	18	50	21	23	07	00	19	29			
57	24	20	30	27	27	24	16	43	30	20	19	14	28	28	22	25		
58	11	08	15	18	08	16	12	17	21	23	00	00	31	19	14	08	25	

Table 8.14 : Summary Mean IS (%) Matrix Data.

	Mt.Rae	Mt.Allan	Parkers Ridge
Mt.Rae	44.8	45.0	32.3
Mt.Allan		45.2	26.5
Parkers Ridge			18.9

although wetter sites illustrate remarkable coverage by bryophytes (eg. Lobes 5, 37). Forbs (*Astralagus alpinus*, *Smelowskia calycina*) and bryophytes dominate most of the riser surfaces (see Appendix V).

Parkers Ridge Area

In the Parkers Ridge area the floral characteristics of the various solifluction lobes appear to be dependent upon individual site characterisitcs (see Appendix V). While *Salix arctica* dominates many of the sites (eg. Lobes 49-56), *Salix reticulata* was much more significant at others (eg. Lobes 62, 63). At the south-facing sites, forb (*Antennaria lanata*, *Erigeron aureus*) and gramminoid (*Poa alpina*; *Trisetum spicatum*) communities dominate.

8.4.4.2 Results

The vegetation cover of turf-banked solifluction lobes is considered to be an important index of solifluction activity. Evidence from previous studies has shown that certain species are tolerant of solifluction motion, while other species are generally intolerant to any form of solifluction and will not survive where solifluction processes are active (Dahl, 1956; Carbiener, 1966; Raup, 1969). To examine the nature of this relationship in the present study, community coefficients from each of the lobe zones were ordinated together. This provided a measure of zonal similarity which was then used to recognize prominent vascular plant species which might index solifluction motion. Because the Parkers Ridge data proved to be so floristically dissimilar, they were excluded from the following analysis.

Zonal Vegetation

The general similarity in flora found at solifluction lobes within the Mt Rae and Mt.Allan areas prompted a within-site survey of species distribution. Only vascular species were considered, and they illustrated remarkable species richness (percentage of the total number of vascular plant species surveyed). In both study areas the lobe front zone exhibited the highest values (78 percent), while the lobe rise (74 percent) and tread (74 percent) zones had only slightly lower values.

a) Zone A (lobe front):

Indirect ordination of the vascular species surveyed in the lobe front (IS = 41.9%) indicated moderate clustering (Figure 8.11a). The most prominent species of this zone (see Appendix VI) were *Salix arctica* (216.20), *Antennaria lanata* (98.20), *Vaccinium scorparium* (83.98), *Juncus drummondii* (67.58) and *Salix reticulata* (67.36) (Table 8.15).

b) Zone B (lobe riser):

The lobe riser zone was floristically the most diverse (IS = 31.5 %), even without considering the many bryophytes, which in some instances dominated the community structures (see Appendix VI). This point was borne out by the spatial separation of the dissimilarity values illustrated by indirect ordination (Figure 8.11b). Amongst the most prominent shrubs of this zone were mat-forming clumps of *Salix reticulata* (155.21) and *Vaccinium scoparium* (65.48) (Table 8.15). The prominence of the perennial herb *Astralagus alpinus* (79.37) and *Oxyria digyma* (62.00), and the various mosses (109.00), are indicative of the generally moist character of this zone.

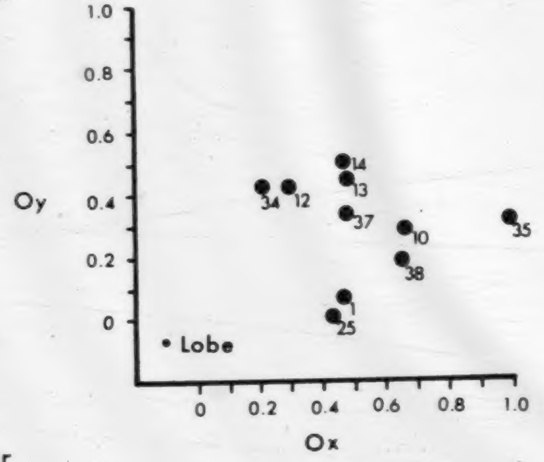
c) Zone C (lobe tread):

Great floral diversity was indicated within the tread zone (IS = 34.0 %), where spatial separation of the indirect ordination values was large (Figure 8.11c). Dwarf shrubs (*Salix reticulata* (PV = 183.61), *Salix arctica* (165.36), *Phyllodoce aleutica* (86.16), *Dryas octopetala* (76.07) and the perennial herb *Antennaria lanata* (116.00) were amongst the most prominent species found on the lobe treads (Table 8.15). The percentage cover by forbs and grammoids, prominent in the other two lobe zones, was considerably reduced on most of the lobe treads (see Appendix VI).

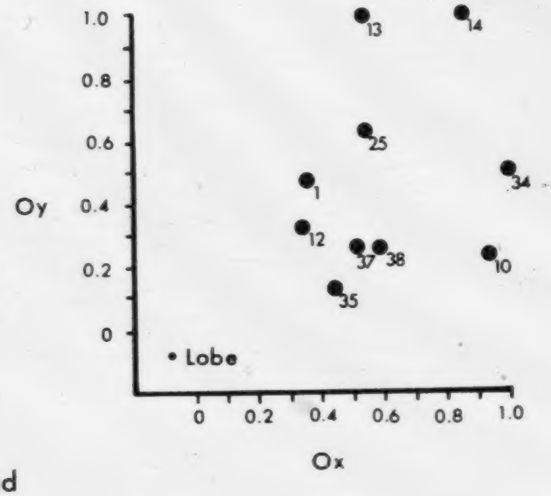
8.4.5 Discussion

Vegetation cover has often been identified as one of the most important parameters controlling solifluction (Seidenfaden, 1931:5; Warren-Wilson, 1952:296; C.Harris, 1973:26). Gamper (1983:329), for instance, discovered relatively high rates of solifluction activity on

a) Lobe Front



b) Lobe Riser



c) Lobe Tread

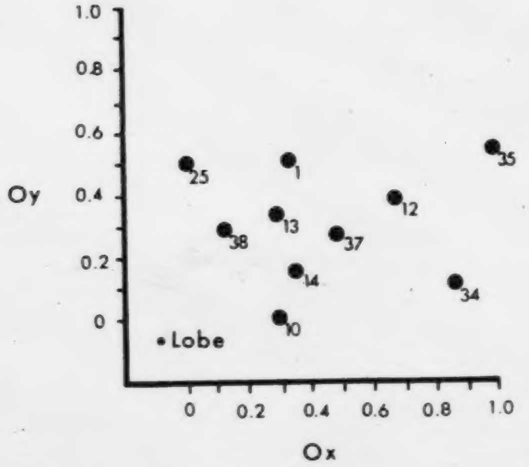


Figure 8.11 : Two dimensional ordination of the vegetational quadrat data.

Table 8.15 : Summary of significant plant species located within each lobe zone as indicated by their prominence value (PV)[1].

SPECIES	Zone A	Zone B	Zone C
Dwarf Shrubs			
Dryas octopetala	40.09	9.26	76.07
Phyllodoce aleutica	47.81	0.00	86.16
Salix arctica	216.20	60.40	165.36
Salix reticulata	67.36	155.61	183.61
Vaccinium scoparium	83.98	64.48	41.16
Forbs			
Antennaria lanata	98.20	49.20	116.0
Arnica mollis	50.80	22.45	0.37
Astragalus alpinus	37.80	22.45	8.35
Castilleja occidentalis	7.78	18.33	10.04
Erigeron peregrinus	0.00	15.40	24.26
Oxyria digyma	8.83	62.00	0.26
Potentilla diversifolia	23.15	21.10	34.57
Saxifraga rhomboidea	9.26	18.47	0.26
Selaginella densa	4.16	37.42	29.78
Silene acaulis	18.57	0.46	11.04
Smelowskia calycina	8.96	12.74	30.00
Graminoids			
Carex nigricans	11.31	1.80	19.58
Juncus drummondii	67.58	15.00	0.26
Kobresia myosuroides	56.13	45.83	60.00
Phleum alpinum	10.69	0.37	5.29
Poa alpina	17.69	6.30	13.82
Poa arctica	26.48	6.30	20.77
Trisetum spicatum	11.10	0.27	5.65
Bryophytes			
Moss ssp.	53.00	109.00	81.25
Lichens	19.00	38.50	33.74

1. A complete list of PV values for each zone is contained in Appendix VI.

vegetation-free areas but correspondingly slower rates at vegetation-covered sites. In this study, however, there appears to be no correlation between the vegetation cover of a plot and the rate at which it moves downslope. In fact, as Figure 8.12 shows, some of the fastest movements recorded occurred at sites with the greatest vegetation coverage. This observation corresponds to that of Raup (1969), and thus the relationships illustrated by Figure 8.12 may actually signify some form of moisture gradient. However, the fieldwork performed for this study was not sufficiently detailed to demonstrate this point.

The interaction between solifluction and vegetation is more notable when one recognizes the impact recurrent solifluction disturbances have on the composition of plant communities (c.f. Noble and Slatyer, 1980; Jonasson and Skold, 1983). Specifically, this type of exogeneous disturbance tends to result in the gradual emergence and dominance of species adapted to, or tolerant of, these conditions (Dahl, 1956; Raup, 1969). Theoretically, their proportional representation in a plant community should be a function of local solifluction activity.

Initially this suggestion was examined in light of previous investigations of solifluction-vegetation relationships. A literature review revealed 18 studies in which 29 of the vascular species examined in this study had been related to specific solifluction lobe elements. Of these studies five had been completed in close proximity to the present field area (Hrapko, 1970; Trottier, 1972; Knapik et. al., 1973; Kuchar, 1975, Mortimer, 1978). Table 8.18 summarizes the results of this survey and provides an indication of species distribution by lobe zone.

Many of the species included in this review clearly have wide habitat tolerances and are almost universal in their distribution at solifluction lobe sites (eg. *Dryas octopetala*, *Poa arctica*, *Silene acaulais*). Other species appear to be more restricted by the character of individual lobe habitats (eg. *Antennaria lanata*, *Oxyria digyma*, *Sibbaldia procumbens*).

Amongst the vascular species which appear able to withstand active solifluction are *Cassiope tetragona* (Seidenfaden, 1931:5), certain *Cerasitum* ssp. (Raup, 1971:15), certain *Draba* ssp (Raup, 1969:127), *Dryas octopetala* (Tengwall, 1925:741; Seidenfaden, 1931:5),

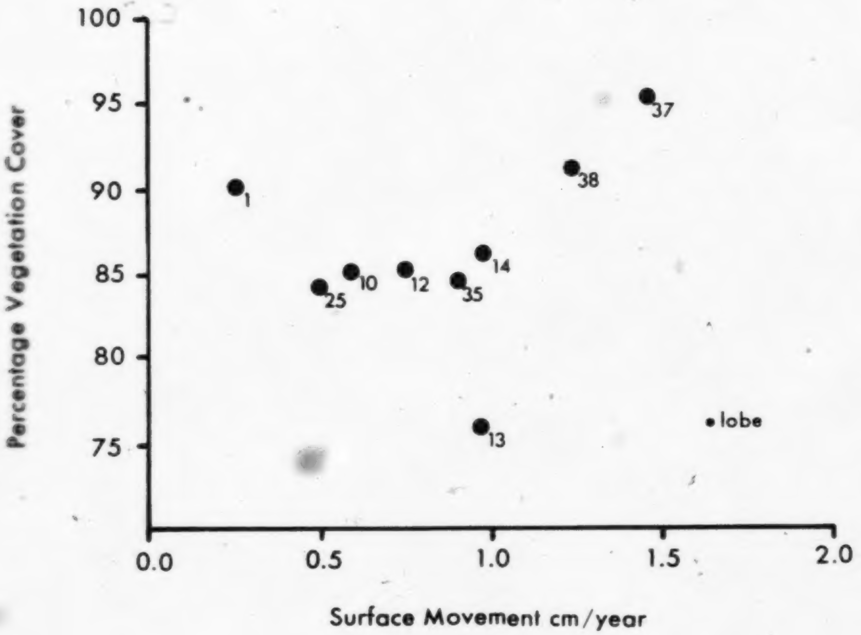


Figure 8.12 : Relationship between vegetation coverage (%) on the tread surfaces and the average rate of surface movement (cm/year).

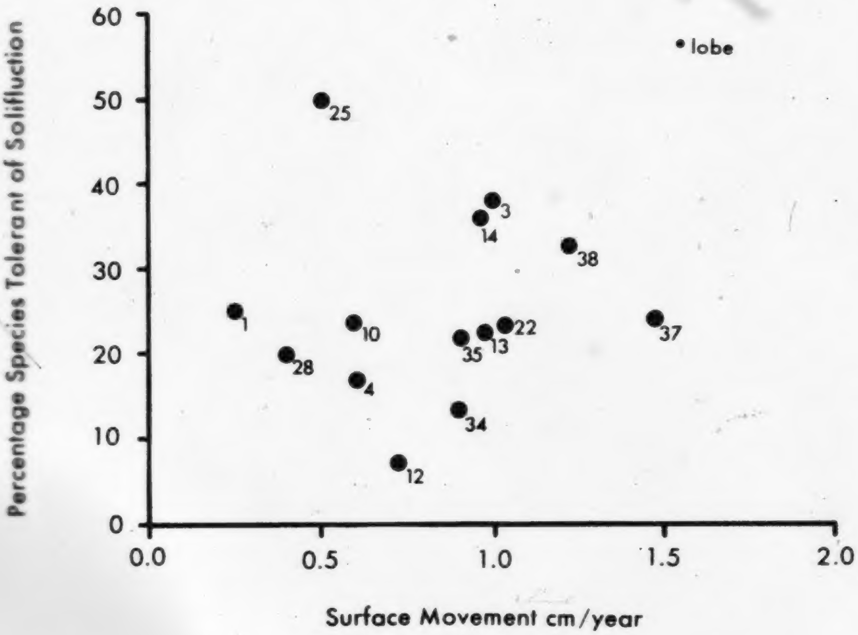


Figure 8.13 : Relationship between percentage of vascular species tolerant of solifluction and the average rate of surface movement (cm/year).

Table 8.16 : Vegetation species recorded elsewhere in association with solifluction lobes which are found within the field area.

Species	Zone A	Zone B	Zone C	Source[1]
Antennaria lanata			+	5, 7.
Astragalus alpinus		+		9.
Carex ruperstris	+	+		1, 11.
Cassiope tetragona	+		+	5, 9, 12, 13, 14.
Castilleja occidentalis		+		9.
Dryas octopetala	+	+	+	5, 10, 12, 13, 15.
Erigeron peregrinus	+	+		5, 9.
Festuca ovina			+	18.
Kobresia myosuroides	+	+		1, 12.
Luzula spicata			+	4.
Oxyria digyma		+	+	10, 11, 12, 13, 17.
Phyllodoce glanuliflora	+		+	5.
Poa alpina	+		+	12.
Poa arctica	+	+	+	12.
Polygonum viviparum	+	+	+	4, 9, 10, 12.
Potentilla diversifolia	+			5.
Potentilla hypartica	+			10, 12.
Salix arctica	+	+	+	5, 9, 12, 13.
Salix reticulata			+	6, 10.
Saxifraga cernua	+		+	12, 17.
Saxifraga lyalli			+	7.
Saxifraga oppositifolia			+	3, 11, 12, 15.
Senecio triangularis		+		5.
Sibbaldia procumbens	+			12, 17.
Silene acaulis	+	+	+	10, 12, 13.
Solidago multirudiata	+			5.
Taraxacum ssp.		+		10, 17.
Trisetum spicatum	+	+	+	2, 10, 12.
Trollius albiflorous	+			5.
Vaccinium scorparium	+			5.

1. Source # : 1)Benedict, 1970; 2)Billings and Mark, 1961; 3)Carbiener, 1966; 4) Dahl, 1966; 5) Hrapko, 1970; 6) Kaiser, 1980; 7) Knapik, et. al., 1973; 8) Kuchar, 1975; 9) Mortimer, 1978; 10) Price, 1970a; 11) Rapp, 1960; 12) Raup, 1969; 13) Seidenfaden, 1931; 14) Soderman, 1980; 15) Tengwall, 1925; 16) Trottier, 1972; 17) Warren-Wilson, 1952; 18) White and Mottershead, 1972.

certain *Juncus* ssp. (Williams, 1957:45), *Luzula spicata* (Dahl, 1956:278), *Oxyria digyma* (Seidenfaden, 1931:6; Warren-Wilson, 1952:259; Rapp, 1960:181), certain *Phyllodoce* ssp. (Dahl, 1956:278; Williams, 1957:48; Carbiener, 1966:360), *Polygonum viviparum* (Dahl, 1956:278; Raup, 1969:127), *Salix arctica* (Seidenfaden, 1931:5), *Salix reticulata* (Kaiser, 1980:124), *Saxifraga cenua* (Warren-Wilson, 1952:301), *Saxifraga lyalli* (Knapik, et. al., 1973:A164), *Saxifraga oppositifolia* (Rapp, 1960:181; Carbiener, 1966:360-361; Raup, 1969:127), and certain *Taraxacum* ssp. (Warren-Wilson, 1952:260; Raup, 1969:127; Price, 1970a:97). The following flora are recognized as intolerant of any degree of solifluction: *Empetrum* ssp. (Dahl, 1956:278; Carbiener, 1966:361), *Sibbaldia* ssp. (Warren-Wilson, 1952:258) and *Vaccinium* ssp. (Dahl, 1956:278; Williams, 1957:45).

According to this survey, 15 (18%) of the 83 vascular flora found in association with solifluction lobes in the field area have this tolerance/adaptation characteristic. Typically, these species composed from 7 to 50 percent of the total number of species present on the tread surfaces of lobes in the Mt.Rae and Mt.Allan areas. However, as Figure 8.13 shows, there was no correspondence between their prominence and surface movement rates. Not only that, but the highest proportion of *tolerant species* was actually detected at one of the slower moving sites (Lobe 37). Similarly, there appears to be no consistent relationship between their representation and volumetric movements. However, as these interpretations are based on ecological relationships which remain obscure (c.f. White, 1979), it may be that the species identified were not in fact reliable indicators of solifluction movement.

A different perspective of the effect solifluction has on plant community composition was shown by indirect ordination. Figure 8.14 demonstrates the relationship between x-axis variation and surface movement rates on tread surfaces. Although no correlations are immediately apparent, by distinguishing the dominant vascular genera two groupings appear. In much the same manner, the relationship between x-axis variation and the maximum depth of solifluction movement only appears significant when the scores are empirically separated (Figure 8.15). However, since these vegetation responses may correspond to nutritional,

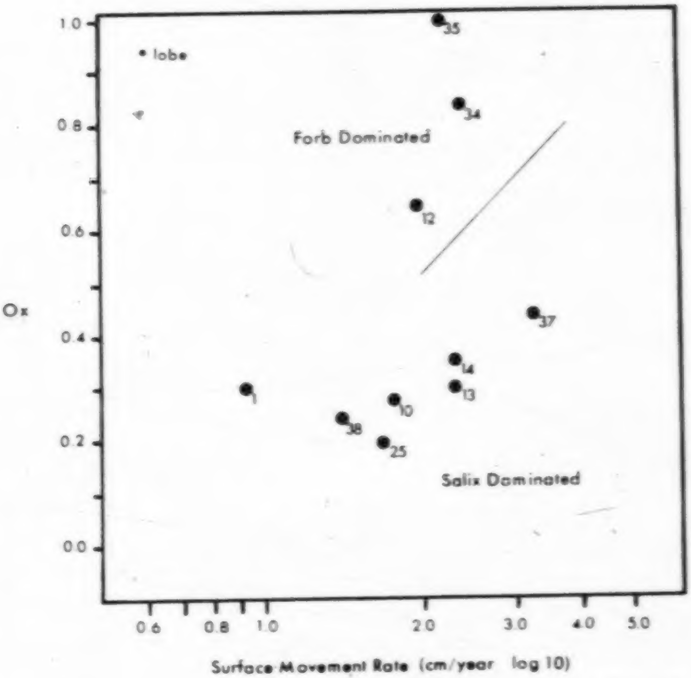


Figure 8.14 : **Surface movement rates (cm/year) as a function of x-axis ordination value of the tread surface.**

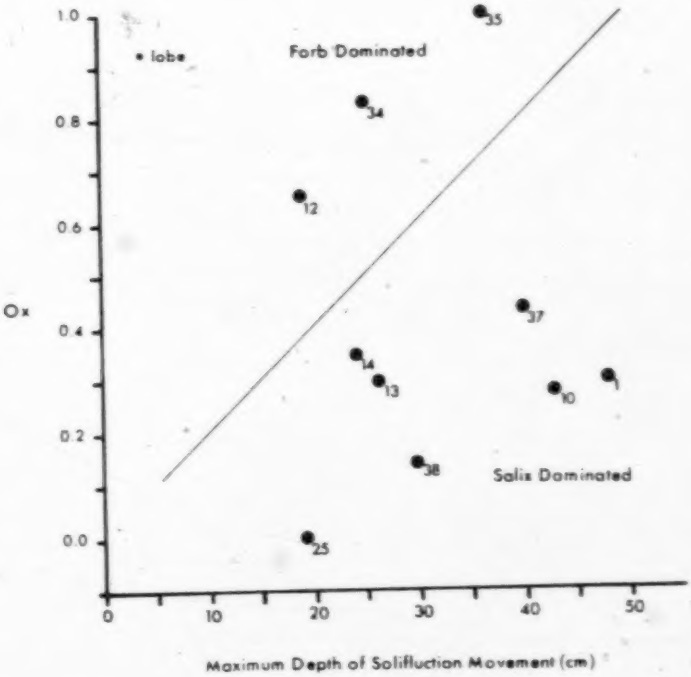


Figure 8.15 : Maximum depth of solifluction movement (cm) as a function of x-axis ordination value on the tread surface.

moisture or pH variations (c.f, Raup, 1969; Jonasson and Skold, 1983), the effect solifluction has on this relationship remains ambiguous.

8.4.6 Solifluction-Vegetation Summary

These investigations of solifluction-vegetation relationships within the field area illustrate that the vascular flora of the turf-banked lobes selected for study are both relatively rich and, in general, quite similar from lobe to lobe. This is particularly apparent within the Mt.Rae and Mt.Allan areas, where an endemic flora was identified. However, despite these similarities, there is little evidence within the data to indicate whether this vegetation cover was affected by, or influenced, the solifluction movements recorded within the field area. The fact that some of the most rapid movements occurred at the best vegetated lobes may indicate there is no significant relationship between solifluction and vegetation. In summary, this survey of the vegetation cover of active solifluction lobes proved, unfortunately, insufficient in scope to enable the formulation of a botanical index of the relative rate of solifluction in the Alberta Rocky Mountains field area.

8.5 Conclusions

The character of the contemporary solifluction movements monitored within the Alberta Rocky Mountains region by this study were ultimately dependent upon the influence of a plethora of environmental parameters. The investigations described within this chapter attempted to elucidate the specific effect of several of these parameters.

The results of these analyses demonstrated several things. First, it was established that, within this area, solifluction lobes occurr mostly on moderately sloping, northeast-facing slopes, located in close proximity to the present-day treeline. Secondly, it was shown that, in general, the sediment which composed these lobes had little discernible impact on the rate of solifluction measured. It was recognized, however, that the areal similarity of these sediments did preclude the likelihood that any significant differences would be illustrated. Thirdly, there was little evidence suggesting that differences in the climate experienced by the three study areas differentially influenced solifluction over the study period. Fourthly, microclimatic investigations carried out within the Mt.Rae area indicated that soil moisture and temperature oscillations were, at least partially, responsible for the slight temporal variations detected in the local rates of solifluction. Specifically, it was shown that these parameters interacted to alter the contributions made by the different solifluction mechanisms. Finally, it was not possible to determine from a survey of the vascular flora of the study lobes, whether or not the vegetation cover of these lobes was influenced by or, in turn, influenced the rate of solifluction.

9. HISTORICAL SOLIFLUCTION ACTIVITY

9.1 Introduction

Evidence of historical solifluction lobe activity within the Alberta Rocky Mountains is very limited. Despite this paucity, there are indications that solifluction has been an active geomorphic process in this region for a considerable period of time. For example, Ford (1979) described solifluction lobes within the Castleguard Valley of northern Banff National Park, which he believed were initiated at the beginning of the most recent Neoglacial period. Similarly, D.Smith (1979) described two solifluction lobes near Highwood Summit in southeastern Kananaskis Provincial Park which had overrun solum capped by volcanic ash of likely Mazama age (6600 years BP). While, these observations suggest that solifluction has a long history of activity within this region, they have done little to substantiate the long-term behavior of solifluction.

The aim of the research discussed in this chapter was to evaluate the past rates of solifluction within the Mt.Rae area. No attempt was made to examine the past activity of solifluction in either the Mt.Allan or Parkers Ridge areas where, historically, solifluction may have behaved quite differently. In the Mt.Rae area these investigations focused on two adjacent turf-banked solifluction lobes. Trenches dug into both lobes revealed continuous buried organic layers overridden by the advancing lobes. These deposits were radiocarbon dated and used to calculate the long-term, average rates of lobe movement. In order to establish an absolute chronology of these movements and relate them to paleoclimatic change, it was necessary first to determine the radiocarbon ages of these deposits at the time of burial.

9.2 Location and Setting

The two lobes chosen for study, Lobes 1 and 25, are located within Tombstone Valley in the Mt.Rae area (see Figures 4.1 and 4.4) at approximately 50° 40' 15" N latitude and 115° 01' 30" W longitude. Both occur on a northwest-facing alpine tundra slope with a gradient ranging from 6 to 14°. The slope consists of a glacially smoothed bedrock knoll composed of Rundle Group limestones and dolomites (Ollernshaw, 1975) mantled by a silty, calcareous glacial till (Jackson, 1977). Deglaciation is estimated to have occurred about 12,000 years BP (Jackson, 1980), with later early-Holocene glaciers terminating less than 0.5 km from the site (Smith, 1979; Gardner, et. al., 1983).

Solifluction lobes within Tombstone Valley were selected for intensive study primarily because, unlike the situation at most of the neighbouring sites, the arrangement of the local bedrock ensured this headwater valley has remained immured from coal deposits which can seriously contaminate radiocarbon samples (c.f. Scharpenseel and Schiffmann, 1977a; J.Matthews, 1980). Unfortunately, as is characteristic of virtually all of the Alberta Rocky Mountains field area, the calacareous nature of the local drift means there was still a possibility of sample contamination by inorganic carbonates (c.f. Scharpenseel and Schiffmann, 1977b; Ellis and Matthews, 1984).

9.3 Description of the Study Sites

The two solifluction lobes are situated in close proximity to one another (Figures 9.1 and 9.2). Lobe 1 is located at an elevation of 2370 m asl on a slope of 14° and with a 307° aspect (see Table 5.4). It is greater than 10 m across at its widest point, and is distinguishable over a length of a least 15 m. The gently sloping upper tread surface (7.5°) is largely vegetated by a *Salix reticulata / Phyllodoce aleutica / Salix arctica* community, although *Phyllodoce* does dominate the eastern edge of the tread surface (Figure 9.3). The steep tread riser, 0.31 m in height, is mantled by a lichen / bryophyte / *Arnica mollis* community. In front of the leading edge of the lobe a *Salix arctica / Arnica mollis / Juncus drummondii* plant community is developed above an Orthic Melanic Brunisol. Observations over the research period (1980-1982) indicated that solifluction averaged 0.25 cm/year on the tread surface of this lobe, annually transporting 9.8 cm^3/cm/year of sediment (see Table 6.2).

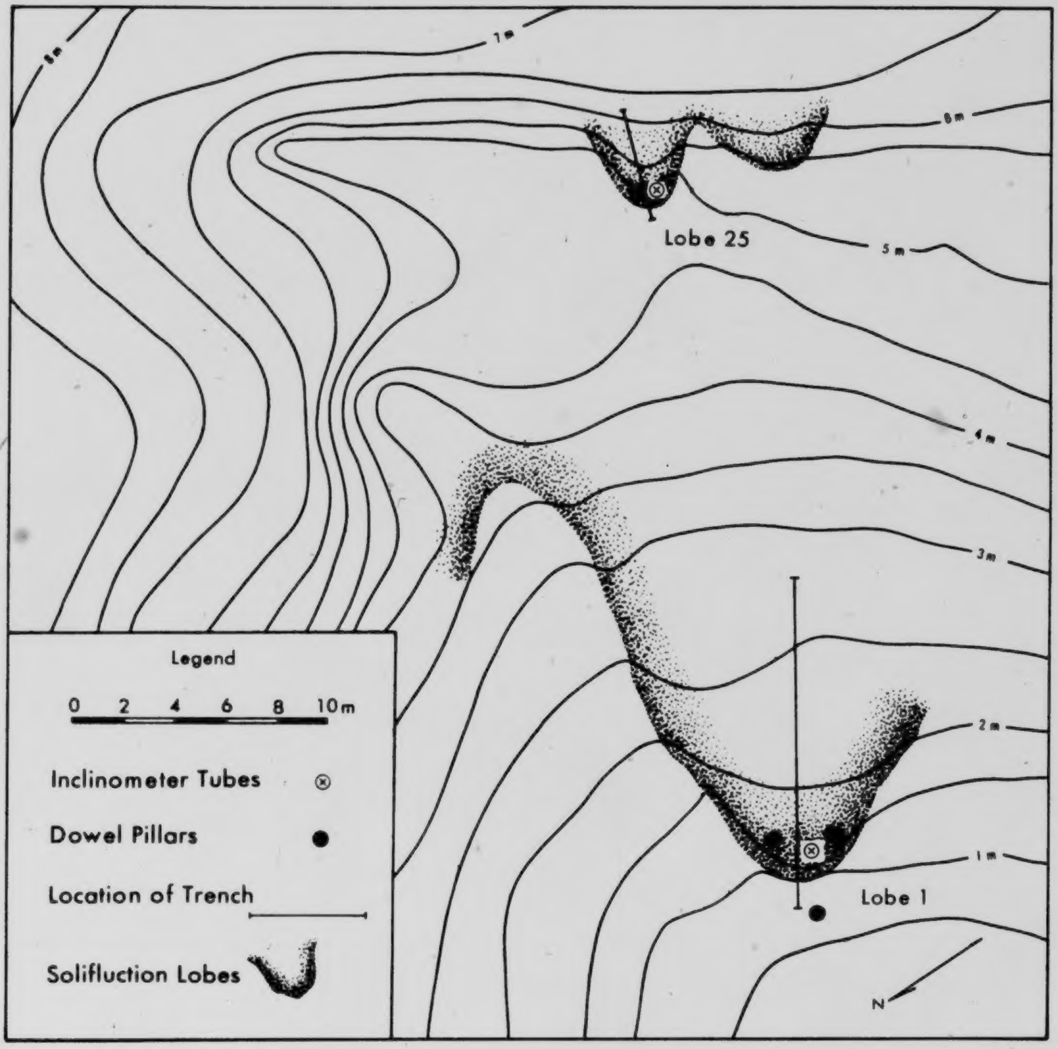

8m
7m
6m
Lobe 25
5m
4m
3m
2m
1m
Lobe 1
N
Legend
0 2 4 6 8 10m
Inclinometer Tubes ⊗
Dowel Pillars ●
Location of Trench
Solifluction Lobes

Figure 10.1 : Topographic setting of Lobe 1 and Lobe 25 at the Tombstone Valley site in the Mt.Rae area.

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Figure 9.2 : Physical setting of Lobe 1 (lower arrow) and Lobe 25 (upper arrow) at the Tombstone Valley site.

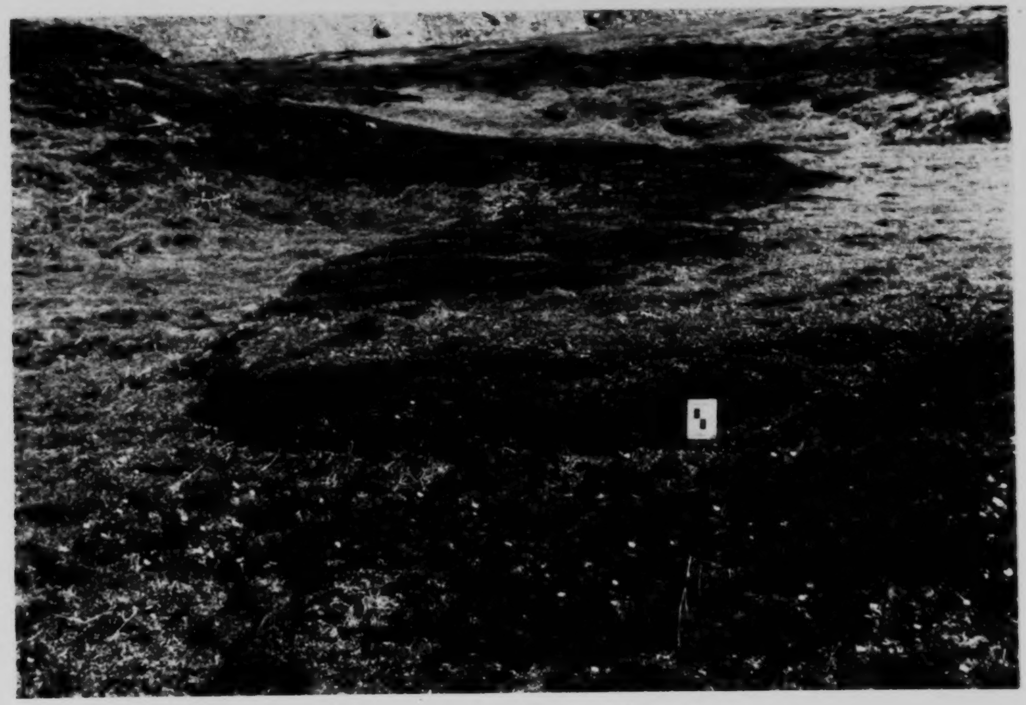

Figure 9.3 : Lobe 1 at 2370 m asl in Tombstone Valley. Note the field notebook for scale.

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Images en couleur

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Lobe 25 (Figure 9.4), is situated 20 m upslope from Lobe 1 at 2373 m asl (Figures 9.1 and 9.2). It has an aspect of 287° and sits on a 6° slope (Table 5.4). Less than 5 m in length and, at its widest point, only 5.1 m across (see Figure 4.11), its moderately dipping upper tread surface (14°) is vegetated by a *Salix arctica/Salix reticulata* assemblage. On its frontal snout, which rises approximately 0.24 m above the parent slope, *Salix reticulata* and a variety of bryophytes dominate the vegetation cover. The lobe is encroaching upon an Orthic Melanic Brunisol vegetated by a *Salix reticulata* community. Contemporary solifluction movements at Lobe 25 (1980-1982) averaged 0.50 cm/year on the tread surface, transporting approximately 10.20 cm^3/cm of sediment on an annual basis (see Table 6.2).

COLOURED PICTURES
Images en couleur

Figure 9.4 : Lobe 25 at 2373 m asl in Tombstone Valley.

9.4 Methods

Trenches were dug into both lobes to permit detailed stratigraphic mapping and sediment sampling. These 0.5 m wide trenches began 0.5 m in front of each tread riser and extended perpendicularly upslope into each lobe, 10.5 m at Lobe 1 and 4 m at Lobe 25 (Figure 9.1). After logging the exposed sections, sediment sampling at 0.5 m intervals was undertaken. Careful attention was directed towards ensuring the trenches extended at least 25 cm below the lobe base, into undisturbed underlying slope sediments. Analysis of these sediments followed the standardized procedure outlined previously (see Section 5.4). In addition, soil pH was measured with an electrode in a water saturated soil paste (McKeague, 1978 : 3.14). Bulk samples collected for radiocarbon analysis were air-dried and carefully examined microscopically to remove any rootlets. They were then submitted to the Brock University Radiocarbon Laboratory (BGS) for radiocarbon dating.

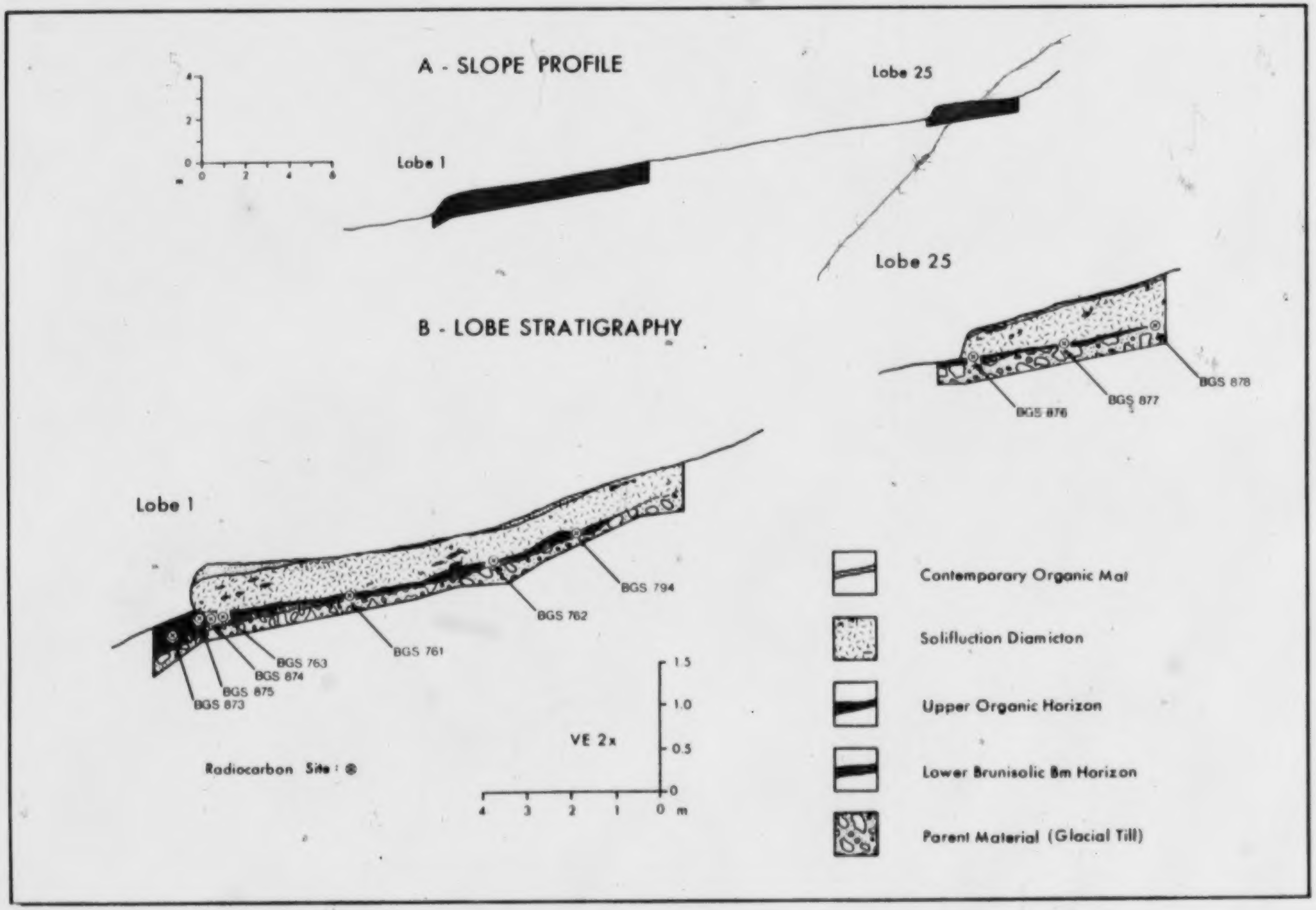
9.5 Results

9.5.1 Stratigraphy

Both lobes terminate above a soil pedon overridden by their advance. Downslope of the tread risers these horizons are continued as part of the present solum. Excavation of these lobes was completed in July, 1980, at Lobe 1 and August, 1982, at Lobe 25. The sections revealed by these investigations are portrayed in Figure 9.5.

9.5.1.1 Lobe 1

At Lobe 1 a buried organic layer extended some 9.1 m upslope from the present snout position. The solifluction sediment resting on this buried soil had a silty texture with no apparent structure (Figure 9.6). While thickening slightly downslope, there was little evidence of longitudinal sorting within the lobe. The limited number of pebbles and small stones discovered were widely scattered, illustrating only slight concentrations (Figure 9.5). At the surface of the lobe, organic matter accumulations had formed a thin, discontinuous horizon.


A - SLOPE PROFILE
4
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0
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2
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6
m
Lobe 1
Lobe 25
B - LOBE STRATIGRAPHY
Lobe 25
BGS 876
BGS 877
BGS 878
Lobe 1
BGS 873
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BGS 874
BGS 763
BGS 761
BGS 762
BGS 794
Radiocarbon Site : ⊛
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Upper Organic Horizon
Lower Brunisolic Bm Horizon
Parent Material (Glacial Till)

Figure 9.5 : Slope profile and statigraphy at the sites of Lobe 1 and Lobe 25.

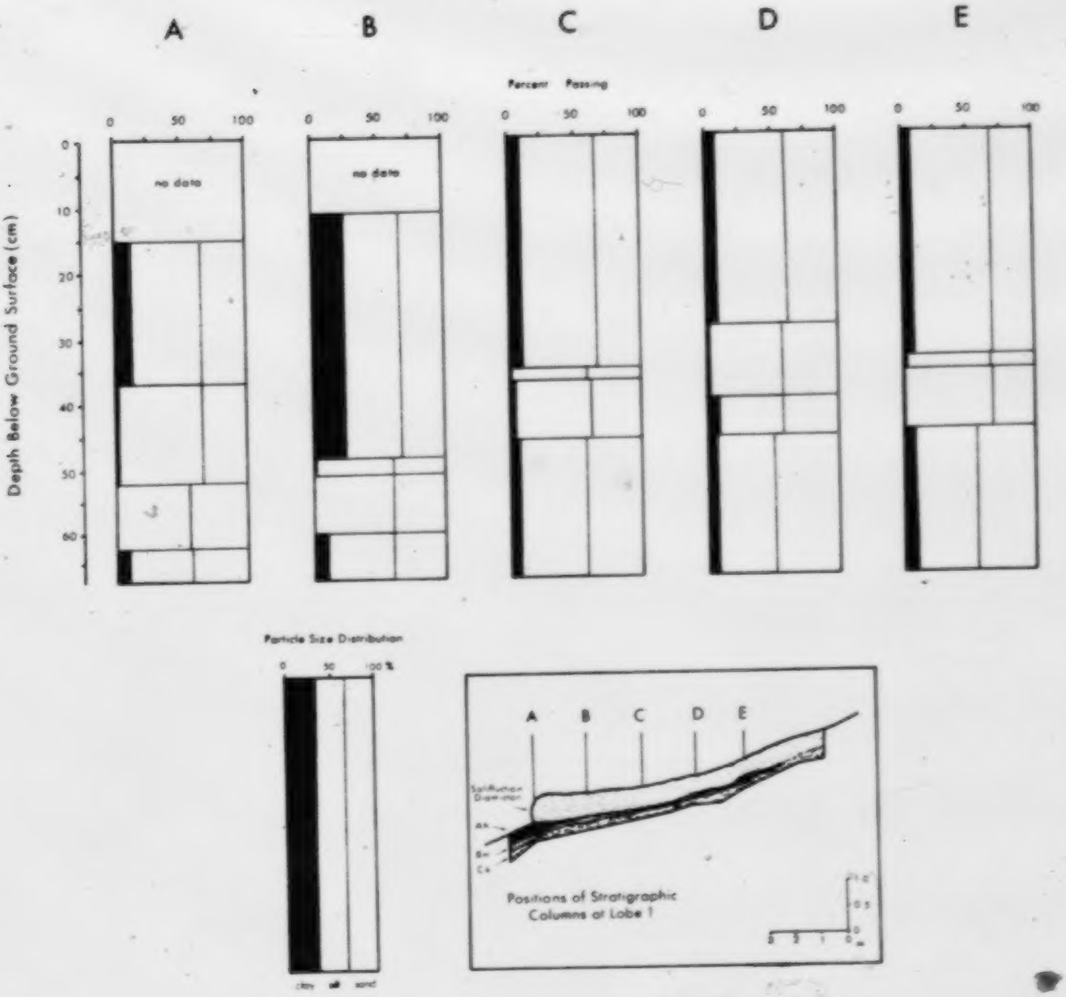

Figure 10.6 : Percentages of clay/silt/sand in the less than 2.00 mm size fraction at stratigraphic columns in Lobe 1.

The soil buried by the advancing lobe was continuous with the modern Orthic Melanic Brunisol. Throughout the length of the trench two horizons were discernible, an upper black organic-rich Ah horizon and a lower reddish-brown Bm horizon. Although these horizons become thinner and less distinct upslope of the lobe front, apart from some compaction of the upper layer, they appeared undisturbed by the advancing lobe.

The buried Ah horizon contained small amounts of clay, within a predominantly silty matrix (Figure 9.6). This layer remained quite friable despite having a compacted appearance. While modern rootlets did invade this layer, their presence was uncommon. Soil pH values established for this horizon demonstrated a slight downslope acidification (Figure 9.7).

Beneath the buried Ah horizon was a laterally continuous Bm layer. This horizon deepened from less than 1 cm at its uppermost exposure to 10 cm at the lobe front. Accompanying these morphological changes were downslope losses of clay-sized particles (Figure 9.6) and a drop in pH values (Figure 9.7). This increase in thickness downslope seems to reflect the effect of time on B horizon development, although the possibility of catenary influences cannot be completely ignored (c.f. Abtahi, 1980; Mahaney and Sanmugadas, 1983). The underlying parent material consisted of a massive greyish-brown till with a silty-loam matrix (Figures 10.6 and 10.7).

9.5.1.2 Lobe 25

The section at Lobe 25 was morphologically similar to that at Lobe 1. An organic layer, continuous with the present Ah horizon, was traced back 4 m from the lobe front to the head of the trench where, although it had not failed, it had thinned considerably (Figure 9.5). The solifluction sediment overlying this layer was a silty loam (clay 6%, silt 50%, sand 44% in the less than 2.00 mm fraction) containing only a limited number of subangular pebbles and cobbles. These were largely concentrated just below a shallow turf layer which mantles the tread surface (Figure 9.5).

Similar to the adjoining contemporary pedon, the buried solum consisted of two horizons. The upper organic horizon was relatively thin and dominated by silt (clay 1%, silt

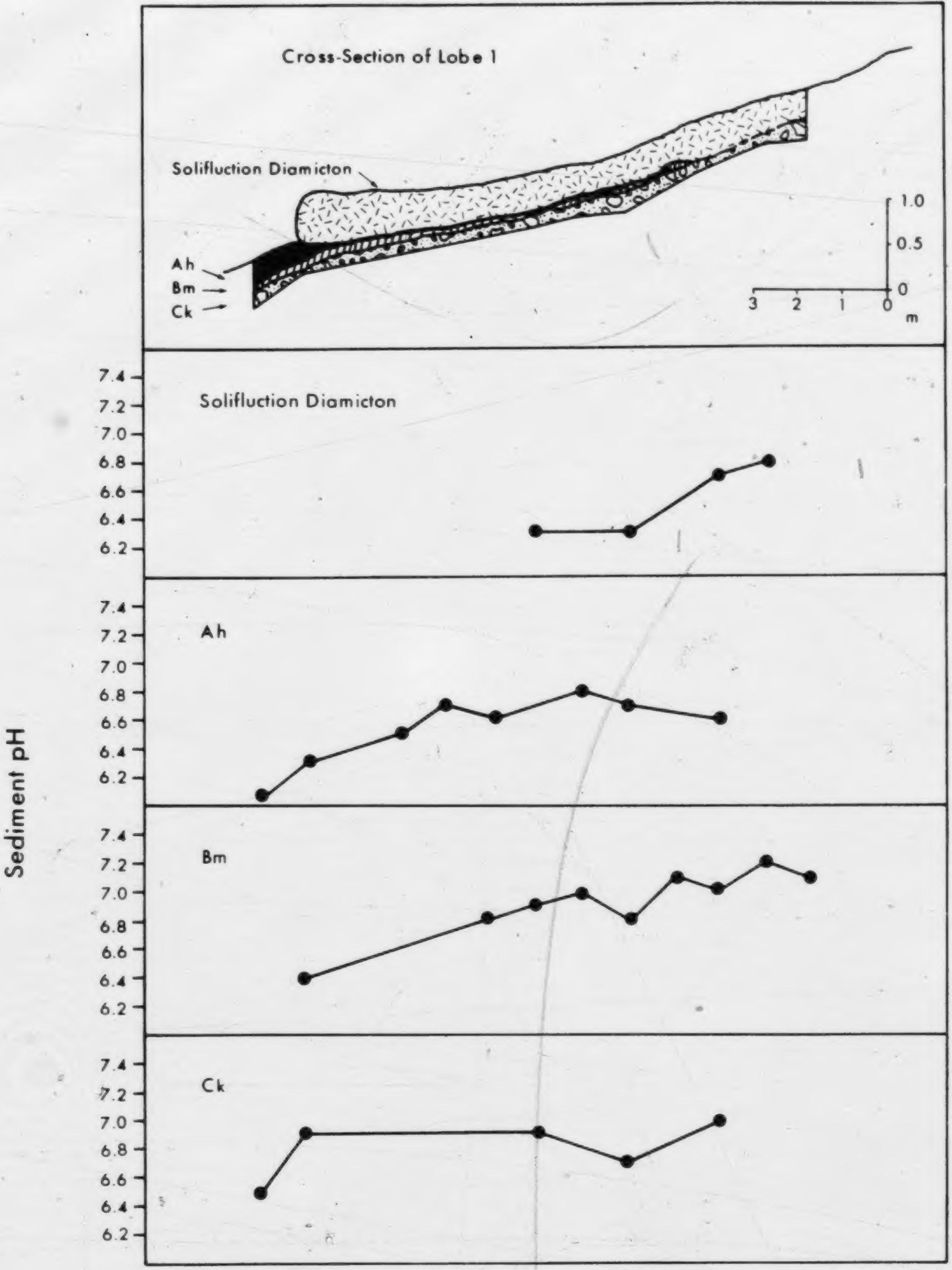

Figure 10.7 : Soil pH relationships at Lobe 1.

67%, sand 31%) in the less than 2.00 mm fraction. The underlying Bm horizon was thin, and in places, ill-defined (Figure 9.5). The silty till parent material at this location appeared identical to that at Lobe 1.

9.5.2 Radiocarbon Dating

In total, ten radiocarbon age determinations were completed for this study. Nine of these were determined on bulk samples taken from the entire thickness of the buried organic layer, from six locations at Lobe 1 and three locations at Lobe 25 (Figure 9.5). To establish the primary phase of soil formation at Lobe 1, the radiocarbon age of the lower component of the modern Ah horizon, 0.5 m in front of the lobe snout, was determined.

The radiocarbon determinations obtained were corrected for laboratory errors reported by Blake (1983:471). No attempt was made to correct these determinations to account for Holocene variations in the radiocarbon content of the atmosphere because of the continuing controversy surrounding the establishment of a universal calibration scheme (c.f. Gulliksen, 1980). In addition, there appears to be little foundation for concerns about minerogenic carbon contamination, as tests completed in the laboratory did not detect free carbonates (Melville, personal communicaton, 1982).

9.5.2.1 Lobe 1

The locations at Lobe 1 where the radiocarbon samples were established are shown in Figure 9.5. Normally, the progressive burial of an organic horizon by a slowly advancing solifluction lobe results in a sequence of radiocarbon dates which get progressively younger towards the lobe front (Worsley and Harris, 1974; Reanier and Ugolini, 1983). However, this time-distance relationship was not fully apparent at Lobe 1 (Table 9.1), where the two foremost dates (2860 ± 100 years BP at BGS-875 and 2250 ± 100 years BP at BGS-874) proved to be considerably older than the radiocarbon date of 1750 ± 100 years BP obtained approximately 50 cm upslope at BGS-763 (Figure 9.5). Without further explanation, all that can be stated for Lobe 1 at this point is that organic matter first began to accumulate at this

Table 9.1 : Radiocarbon ages of buried and modern soils at Lobe 1.

sample[1]	distance from snout (m)	uncorrected C^{14} age (yrs BP)
BURIED SOIL		
BGS-875	0.10	2860 ± 100
BGS-874	0.19	2250 ± 100
BGS-763	0.69	1750 ± 100
BGS-761	4.19	2500 ± 100
BGS-762	7.19	3370 ± 100
BGS-794	9.19	3500 ± 100
MODERN SOIL		
BGS-873	0.50	2900 ± 100

1. for sample site locations see Figure 9.5.

Table 9.2 : Radiocarbon ages of buried soils at Lobe 25.

sample[1]	distance from snout (m)	uncorrected C^{14} age (yrs BP)
BGS-876	0.25	1030 ± 100
BGS-877	2.00	1500 ± 100
BGS-878	4.00	1800 ± 100

1. for sample site locations see Figure 9.5.

site approximately 3500 ± 100 years BP (BGS-794) and was progressively buried over the next 2750 ± 100 years (3500-1750) by the slowly advancing lobe front.

9.5.2.2 Lobe 25

The relationship between time and distance was confirmed at Lobe 25. The samples dated at this site were collected at the locations indicated in Figure 9.5. Here the dating results (Table 9.2) indicate that the lobe advanced 4 m in a 770 year period.

9.5.2.3 Solifluction Rates

In order to obtain an estimate of the long-term rates of advance of these two lobes, the distance between pairs of radiocarbon dates were divided by their age difference (Dyke, 1981:18). Summarized together, these values provided an average measure of overall basal movement rates against which corrected determinations could later be evaluated. These results are summarized in Table 9.3.

The long-term rate of frontal advance at Lobe 1 was estimated from the uppermost radiocarbon dates (BGS-763, BGS-761, BGS-762, BGS-794; Figure 9.5), where the relationship between time and distance was best preserved. This analysis indicates that Lobe 1 advanced at an average rate of just over 0.78 cm/year (Table 9.3). This compares to an average long-term rate of activity at Lobe 25 of 0.45 cm/year (Table 9.3). Together, the overall rate described by these uncorrected determinations averages 0.65 cm/year.

9.6 Discussion

Despite the fact that Lobe 1 is considerably larger than Lobe 25, both of these solifluction lobes appear to have advanced in much the same manner throughout their history of activity. Both have progressively buried vegetated surfaces and underlying solum, with little apparent disturbance. In the absence of either complex structures or conspicuous shearing planes within the contained solifluction sediments, it seems reasonable to assume that both lobes have advanced primarily from viscous flowage. In fact, measurements of contemporary

Table 9.3 : Long-term average rates of movement based on the uncorrected radiocarbon determinations.

Lobe	points[1]	distance (mm)		period years	rate (cm/yr)
1	BGS-794 to BGS-762	2000	in	130 ± 100	1.54
	BGS-762 to BGS-761	3000	in	870 ± 100	0.34
	BGS-761 to BGS-763	3500	in	750 ± 100	0.47
25	BGS-878 to BGS-877	2000	in	380 ± 100	0.53
	BGS-877 to BGS-876	1750	in	470 ± 100	0.37

soil movements tend to confirm this suggestion. Displacements at both sites had convex downslope velocity profiles (see Table 5.4) which have been shown to result from plug-like viscous flows (c.f. Jahn and Cielinska, 1974).

The rate at which these lobes advanced in the past can be reconstructed with reference to the radiocarbon ages determined for the buried Ah horizons (Worsley and Harris, 1974; Dyke, 1981; Gamper, 1981). However, because the *apparent age* of these samples actually represents the sum of time since the soil was buried plus the age of the soil at the time of burial (J.Matthews, 1980:190; 1981:474), these *ages* must be corrected before they can be used to evaluate long-term average rates of movement (Ellis, 1983:284). Unfortunately, application of an appropriate panacea is not an entirely simple matter because of the thermodynamic complexity of soil development (Lavkulich, 1969; Pawluk, 1978) and the potential for disturbance during lobe advance (Ellis, 1979; Alexander and Price, 1980).

9.6.1 Soil Ages at the Time of Burial

Calculation of the *age* of these soils prior to their burial requires an assessment of their **apparent mean residence time** (AMRT). This factor represents the average age of the soil

(Campbell, et. al., 1967:81), because in most pedogenic settings the organic matter present is of mixed age (Paul, 1969:63-76). In fact, many soil profiles actually display a steep linear increase in age with depth (Martel and Paul, 1974:501; J.Matthews, 1981:472).

Many observations confirm that the upper part of a pedogenic profile is biologically active and in dynamic equilibrium with the C^{14} of the atmosphere (Scharpenseel and Schiffmann, 1977b:151; Ellis and Matthews, 1984:81). This continuous process of organic turnover results in relatively low radiocarbon ages for thin youthful soils (Benedict, 1966; Ellis, 1979) and for the near-surface layers of deeper organic horizons (J.Matthews, 1981,1984; Matthews and Dresser, 1983:61). In contrast, relatively resistant and immobile organic compounds steadily accumulate within the lower part of the organic horizon where they are gradually excluded from modern processes (Scharpenseel and Schiffmann, 1977b:151; Ellis and Matthews, 1984:81). Recent studies have established that among the oldest fractions of this essentially biologically inert C^{14} are remnants of the primary phase of soil formation (Scharpenseel and Schiffmann, 1977a:163; J.Matthews, 1981:474). As a consequence, the AMRT of a bulk sample of soil is not an absolute measure of time since soil formation, but rather, a product of this steep age/depth gradient.

Estimates of the AMRT of soils situated within environments similar to that within the field area range from a few hundred (Benedict, 1966; Worsley and Harris, 1974; Ellis, 1979; Alexander and Price, 1980), to a few thousand years (J.Matthews, 1980, 1981, 1982; Ellis and Matthews, 1984). Only a few attempts have been made to date buried alpine soil horizons located within the Alberta Rocky Mountains (c.f. Reeves and Dormaar, 1972; Reeves, 1975; Henoch, et. al., 1979), and in only one study has an AMRT value been established. Working in the Sunshine area of Banff National Park, Scotter and Zoltai (1982) described an Orthic Melanic Brunisol with a 0.05 to 0.08 cm thick Ah horizon which had a radiocarbon age of 1680 ± 100 years BP (BGS-696).

9.6.1.1 Discussion

The AMRT of modern soils at the Tombstone Valley sites was determined by extrapolating the rate of lobe front advance described by the radiocarbon dates obtained on the buried soils (c.f. Dyke, 1981). For instance, at Lobe 25 it was assumed that the lobe front had reached its present snout position by travelling at the same rate (0.37 cm/year, Table 9.3) it had moved from BGS-877 to BGS-876 (Figure 9.5). If this indeed was the case, then the lobe reached its present frontal position approximately 67 ± 100 years after it had passed BGS-876. Consequently, the radiocarbon age of this soil at the time of burial was approximately 963 ± 100 years (1030-67 years).

Calculation of the AMRT of the present-day soil at Lobe 1 is complicated by the two foremost radiocarbon samples (BGS-874, -875) which appear to be anomalously old. In contrast, the radiocarbon ages of the remaining four organic matter samples (BGS-761, -762, -763, -794) are in the proper sequence, as they get progressively older away from the lobe front (c.f. Gamper, 1981; Reanier and Ugolini, 1983). This situation probably arose when the upper portion of the buried organic layer was removed as the lobe advanced across the two lowermost sample positions. This has the effect of increasing the radiocarbon ages of BGS-874 and BGS-875 since only the lower, relatively old, organic matter remained to be dated (Ellis, 1979:31; J.Matthews, 1980:197). This precept is supported by the radiocarbon date obtained on the lowermost portion of the modern Ah horizon of 2900 ± 100 years BP (BGS-873).

Despite uncertainties about events in the frontal section of Lobe 1, the AMRT of the contemporary soil at Lobe 1 can still be reliably estimated. For example, because Lobe 1 advanced across BGS-763 (Figure 9.5) less than 1750 ± 100 years ago, BGS-875 and BGS-874 have also been buried for less than 1750 years. Consequently, the AMRT of the modern soil at Lobe 1 must be greater than 500 ± 100 (2250-1750) years to 1100 ± 100 years (2850-1750 years), but less than 1750 ± 100 years. More precisely, if it is assumed that frontal advance maintained the same pace that it had between BGS-763 to BGS-761 (0.47 cm/year, Table 9.3) to its present position, then its AMRT is approximately 1600 ± 100 years.

9.6.2 Evaluation of AMRT and Soil Formation

The large range in the AMRT estimates of these soils, some 673 ± 100 years (1600-963 years), has broad implications. Because some of the parameters involved do effect the estimates of historical movement rates, this section evaluates the most *probable* explanation for this variance.

The pedological environment at both Lobe 1 and 25 is essentially the same. This is probably best reflected in the morphological synonymity of the associated Brunisolic solum. However, despite this overt similarity, the AMRT estimates suggest that the solum at Lobe 25 is considerably younger than that found below Lobe 1. While a variety of factors, including catenary effects (c.f. Martel and Paul, 1974:502-505) and sample contamination (c.f. Griffey and Matthews, 1978:84), could account for these apparent age differences, certain characteristics of the trench section at Lobe 1 suggest that they are related to chronological variations between the two lobes.

Radiocarbon evidence indicates that soil formation at Lobe 1 began by 2900 years BP This was established by dating organic matter preserved near the base of the modern Ah horizon (BGS-873, Table 9.1). However, soil formation probably began much earlier, because the 2900 year date provides only a minimum estimate of the duration of horizon development. This is because organic compounds are annihilated at different rates (Pawluk, 1978:68) and without fractionation, a more specific age for the initiation of horizon formation could not be obtained (c.f. J.Matthews, 1981; Matthews and Dresser, 1983).

The age of horizon initiation at Lobe 1 was estimated by assuming that the lobe had advanced from the uppermost position, where the organic layer could be traced (Figure 9.5), to the position of BGS-794 at the same rate it later moved from BGS-794 to BGS-762 (1.54 cm/year, Table 9.3). Extrapolation of this rate of activity suggests that soil first began developing at this site about 3600 ± 100 years BP Given the same reasoning, it seems likely that the Bm horizon at this site first began to form from 30 to 130 years after the organic matter began to accumulate at this site.

9.6.2.1 Discussion

This interpretation of the absolute age of the Brunisolic solum at Lobe 1 provides a measure to correct for chronological variations in the AMRT of each of the different radiocarbon determinations. This is a necessary adjustment, since J.Matthews (1980:120; 1982:15) has established that the AMRT of a soil is dependent upon its degree of development. Specifically, AMRT values have been shown to increase during soil development, only becoming constant if a soil reaches an equilibrium state (c.f. Birkeland, 1974:130-131). Because a strong linear relationship is observed between Bm horizon depth and time at these sites (Figure 9.8, where $r=0.99$, $r(0.05, 2)=0.95$), it is assumed that the processes developing these soils have *not* yet attained an equilibrium state. On the basis of this evidence it appears that both of these lobes have progressively overrun and preserved contemporaneously developing solum. It is suggested, therefore, that the AMRT of these buried soils may have altered over the period of their development.

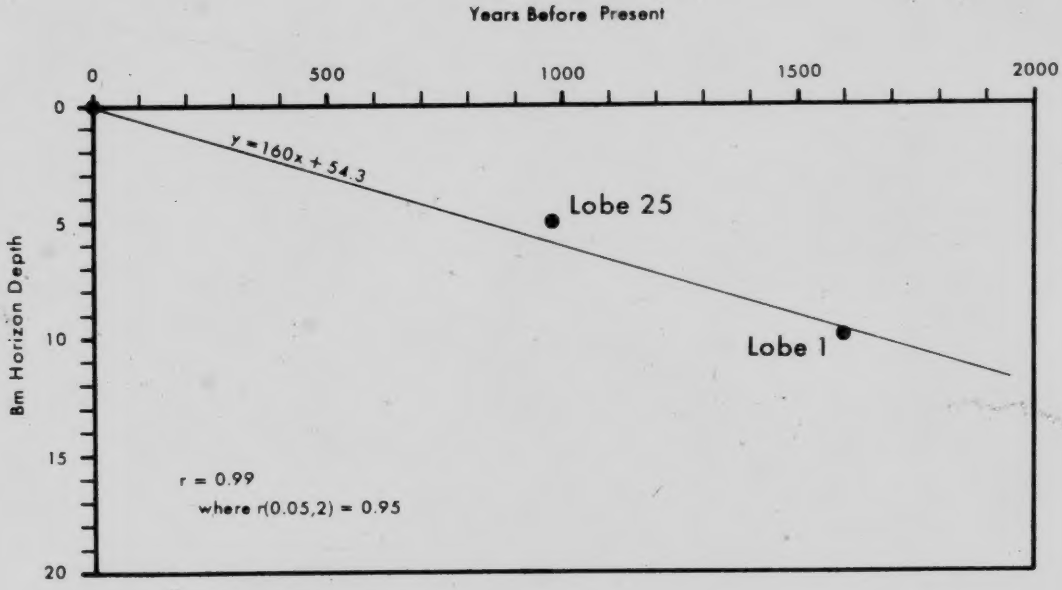

Figure 9.8 : Relationship between Bm horizon depth and the apparent mean residence time of the contemporary soil at Lobe 1 and Lobe 25.

Overall, very little is known about the manner in which AMRT values change over time (c.f. Ellis, 1979:283-284). Although Benedict (1966:29) assumed a constant rate of increase, owing to local variations, this approach almost certainly represents an oversimplification of the problem. There are, however, few realistic alternatives to this interpretation.

The oldest radiocarbon age determinations at Lobe 1 indicate that development of the present Ah horizon began about 3500 year BP Details in the trench suggest that the lobe buried the upslope end of this incipient horizon shortly after that time. If so, it then follows that the organic layer buried at this point should have no apparent age since it must have consisted primarily of living plants overrun by the lobe (Benedict, 1966:28). As the lobe advanced beyond this point, it progressively buried solum of steadily increasing age. Assuming that the AMRT of this buried soil increased at a constant rate from 0 at its inception to 1600 at the present time, a graph can be constructed to correct for the chronological variations in AMRT incorporated within each of the radiocarbon dates determined at Lobe 1 (Figure 9.9).

Although it is not known when soil formation was initiated at Lobe 25, it is suggested that because of its proximity to and pedogenic similarity to the pedological setting at Lobe 1, this can be estimated from the AMRT corrections established for Lobe 1. In this context, the 963 year AMRT noted at Lobe 25 would require soil formation to have begun approximately 2490 years BP. If it is assumed that the AMRT of this soil also increased at a constant rate, a second graph can be constructed to account for the apparent ages of the radiocarbon determinations made at Lobe 25 (Figure 9.9).

On the basis of these two corrections lines (Figure 9.9), the corrected (absolute) ages of the buried soils at Lobe 1 and 25 are presented in Table 9.4.

9.6.3 Historical Rate of Movement

The corrected radiocarbon dates presented in Table 9.4 were used to reconstruct the historical rates of solifluction within Tombstone Valley. The rate of frontal advance at Lobe 1 averaged 0.49 cm/year over the last 3500 years (Table 9.5 and Figure 9.10). Apparently the

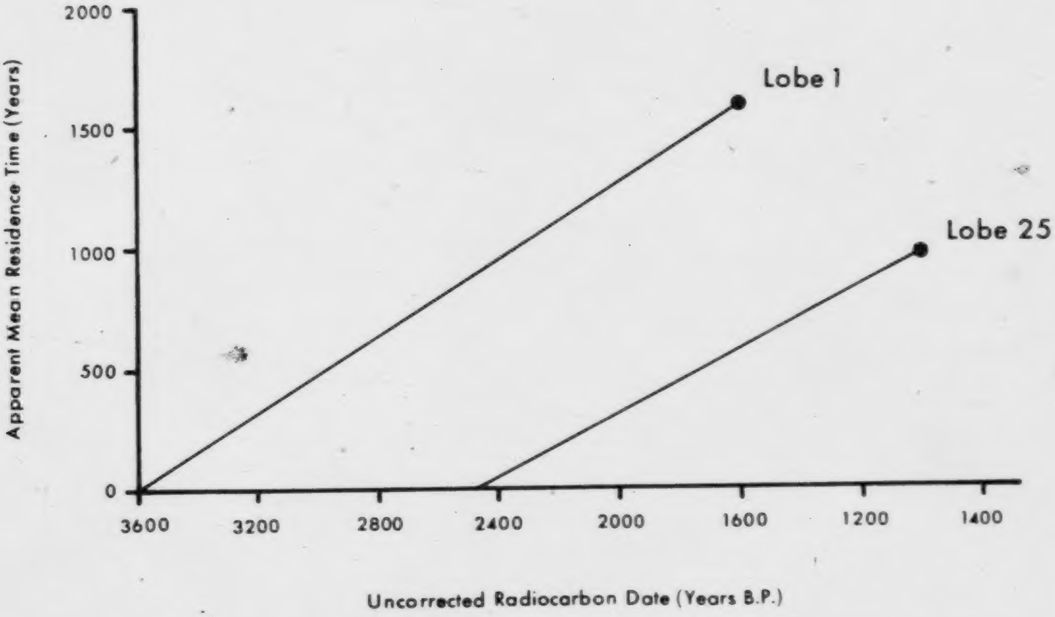

Figure 9.9 : Apparent mean residence time correction graphs established for Lobe 1 and Lobe 25.

Table 9.4 : Corrected radiocarbon determinations derived from Figure 10.9.

sample #	distance from snout (m)	uncorrected C^{14} age (yrs BP)	corrected C^{14} age (yrs BP)
LOBE 1			
BGS-763	0.69	1750±100	270±100
BGS-761	4.19	2500±100	800±100
BGS-762	7.19	3370±100	3186±100
BGS-794	9.19	3500±100	3420±100
LOBE 25			
BGS-876	0.25	1030±100	104±100
BGS-877	2.00	1500±100	667±100
BGS-878	4.00	1800±100	1298±100

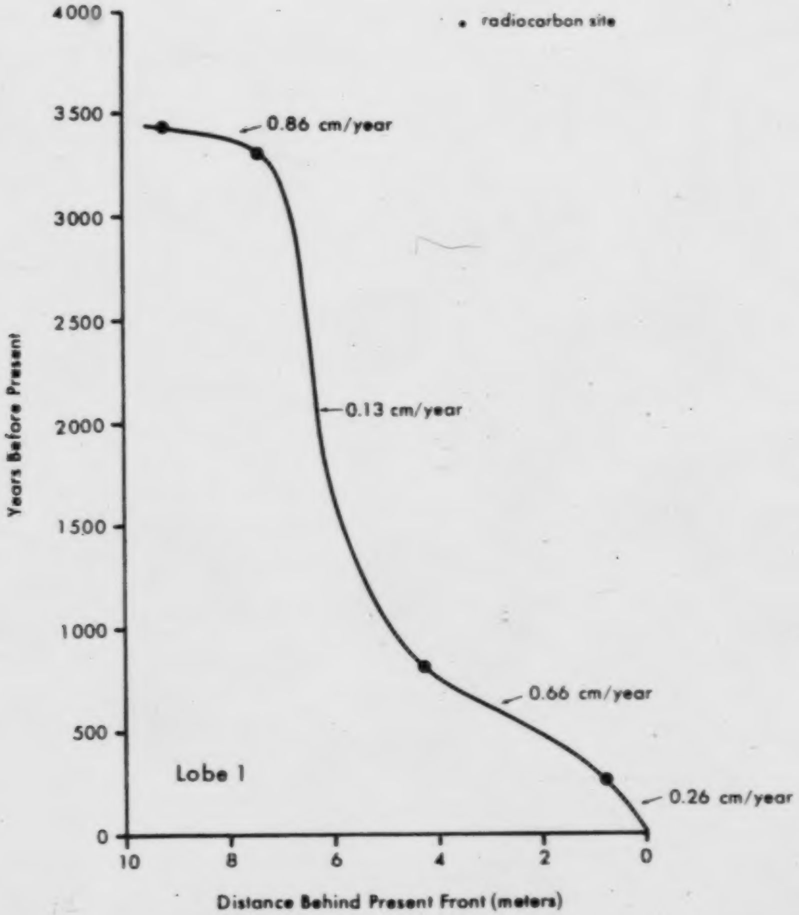

Figure 10.10 : Plot of fluctuations in the rate of advance of the Lobe 1 snout based on the AMRT radiocarbon corrections.

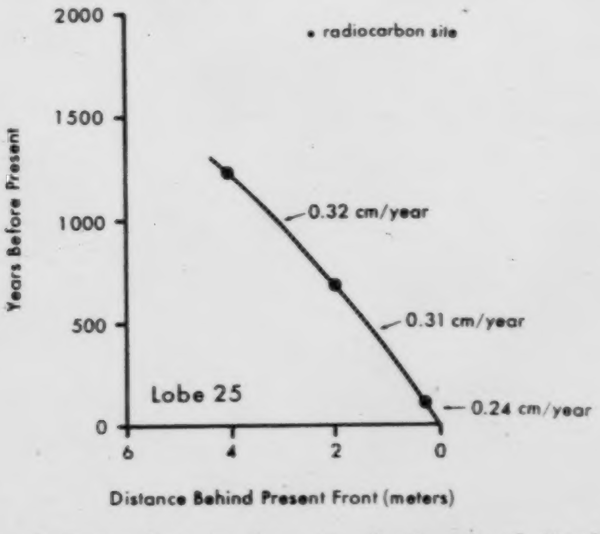

Figure 10.11 : Plot of fluctuations in the rate of advance of the Lobe 25 snout based on the AMRT radiocarbon corrections.

lobe was advancing quite rapidly (0.86 cm/year) when it first began to overrun the incipient soil. However, by about 3200 years BP its rate of advance had gradually declined. Over the next 1800 years, from 3200 to approximately 1400 years BP, the lobe advanced only slowly (0.13 cm/year). After 1400 years BP, solifluction movements gradually increased in magnitude, averaging 0.66 cm/year in the interval from about 800 to 270 years BP Over the last 200 years the rate of lobe movement has once again gradually declined.

At Lobe 25 solifluction rates have averaged 0.29 cm/year over the last 1300 years (Table 9.5 and Figure 9.10) The lobe advanced at an average rate of 0.32 cm/year from 1300 to about 200 years BP Similar to Lobe 1, the last 200 years have been accompanied by a gradual decline in solifluction rates (0.26 cm/year).

Table 9.5 : Long-term average rates of movement based on corrected radiocarbon determinations.

Lobe	point[1]	distance (cm)		period years BP	rate (cm/yr)
1	BGS-794 to BGS-762	2000	in	234±100	0.86
	BGS-762 to BGS-761	3000	in	2386±100	0.13
	BGS-761 to BGS-763	3500	in	530±100	0.66
	BGS-763 to snout	690	in	270±100	0.26
25	BGS-878 to BGS-877	2000	in	631±100	0.32
	BGS-877 to BGS-876	1750	in	563±100	0.31
	BGS-876 to snout	250	in	104±100	0.24

1. for site locations see Figure 9.5.

9.6.3.1 Discussion

Temporal fluctuations in the rate of solifluction activity *may* be related to paleoclimatic changes, since the response history of a given lobe is conditioned by significant fluctuations in temperature or precipitation (Benedict, 1966:30; Gamper, 1983:332). For instance, it is suggested that late-lying snowpacks during cooler episodes promote greater rates of solifluction through more pronounced seasonal saturation of the soil (c.f. Worsley and Harris, 1974; Reanier and Ugolini, 1983). Presumably, during warmer episodes reduced snowpacks, and probably increased vegetational cover, lead to a general decrease in solifluction magnitudes as frost creep mechanisms become more dominant (c.f. Benedict, 1970). On the basis of these observations, an attempt was made to determine to what extent climatic fluctuations in the past may have affected the varying historical rates of solifluction activity established at Lobes 1 and 25.

Unfortunately, the paleoclimatic history of Tombstone Valley remains only inadequately ascribed (c.f. Jackson, 1977; D.Smith, 1979; Gardner, et. al., 1983). For this reason; it was necessary to view the history of solifluction movement rate fluctuation in Tombstone Valley within the context of regional glacial episodes (c.f. Luckman and Osborn, 1979; Osborn, 1982) and climatic changes (c.f. Ferguson, 1978; Kearney, 1981; MacDonald, 1980, 1982). Despite the limitations inherent in a survey at this scale of investigation, there does appear to be a certain synchroneity between the different records. This relationship is summarized in Figure 9.12.

The inferred solifluction record from Lobe 1 suggests that the rate of solifluction movement in Tombstone Valley has varied with changing climatic conditions. This pattern is consistent with the inferred late Holocene glacial record, which is generally considered to provide a sensitive overview of paleoclimatic fluctuations (c.f. Grove, 1979; Porter, 1981).

The early period of very high solifluction rates, between approximately 3500 to 3000 years BP, is presumably related to climatic deterioration accompanying a glacial advance that culminated about 2800 years BP (Jackson, et. al., 1981; Kearney and Luckman, 1981; Leonard,

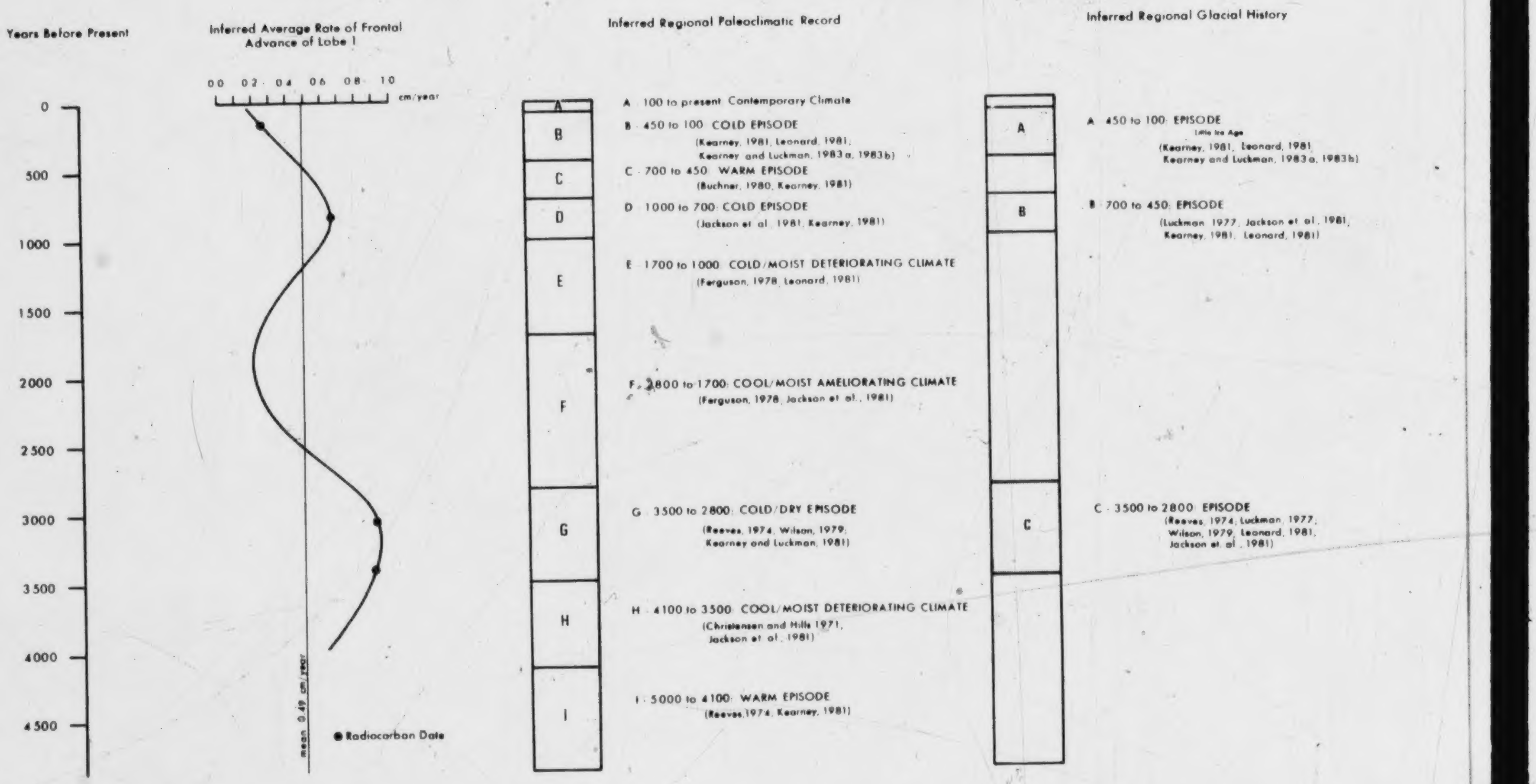

Figure 10.12 : Inferred late-Holocene solifluction, climatological and glacial fluctuations at the site of Lobe 1 in Tombstone Valley.

1981). Solifluction movements during the lengthy interstadial which followed, from 2800 to 1000 years BP, contrast sharply (Figure 9.12). The record from Lobe 1 indicates that solifluction dropped off markedly after 2800 years BP, and did not become significant again until about 1200 years BP The evidence for this behavior is portrayed in Figure 9.10, where it was shown that the front of Lobe 1 only advanced at an average rate of 0.13 cm/year over this interval (Table 9.5). While there is no direct evidence of how much variation there was in this average rate over this lengthy interval, the paleoclimatic boundary established around 1700 years BP (Figure 9.12), is assumed to represent the lowest ebb of this activity. Interestingly, this period of relatively low movements corresponds closely to the interval of soil formation identified at the site of Lobe 25.

The glacial chronology presented in Figure 9.12 indicates that rapid solifluction movements recorded between 1000 to 700 years BP correspond closely in time with a major cooling event marked by maximum glacial stands in the 13th century (Luckman and Osborn, 1979; Leonard, 1981; Kearney and Luckman, 1983a, 1983b). This period was followed by a relatively warm interval until around 400 to 500 years ago (Buchner, 1980; Kearney, 1981), when mountain climates once again entered a cooler period (Kearney, 1981, 1982; Leonard, 1981). Solifluction movements in the latter half of this millennium have steadily decreased showing little response to the latest climatic fluctuation. This apparent lack of synchroneity with the 'Little Ice Age' glacial record, at a time when glaciers were active throughout the Rockies, may reflect a response to different climatic variables (eg. precipitation versus temperature).

9.7 Conclusions

The radiocarbon evidence of historical solifluction activity presented within this chapter indicates that solifluction processes have been active at the Tombstone Valley site for at least the last 4000 years. During that period of time both lobes advanced at varying rates, with contemporary motion close to the slowest recorded.

This history of solifluction activity provides a relatively long-term perspective on the activity of solifluction in one area of the Alberta Rocky Mountains. Unfortunately, its general applicability to the rest of the field area cannot be evaluated without further study.

10. SUMMARY AND CONCLUSIONS

Prior to this research program there was little appreciation for either the character or significance of solifluction within the Canadian Rocky Mountains. In fact, surprisingly few researchers had attempted to elucidate the nature of any of the slow mass wasting processes active in this high mountain setting. This prompted an expansive field investigation whose primary aim was to characterize solifluction at a variety of turf-banked solifluction lobe sites.

This research into solifluction mass wasting had three basic objectives. The first, and primary, objective was to document and characterize the nature of contemporary solifluction. The second objective was intended to complement the first, so that some understanding of the biophysical and environmental context of contemporary solifluction transport was realized. The final objective was to gain some appreciation for the character of historical solifluction activity within this region.

In order to accomplish these objectives, representative research sites were identified within three areas of the Alberta portion of the Canadian Rocky Mountains. Research activities at each of these sites were restricted to a total of 58 turf-banked solifluction lobe plots. These landform deposits were both abundant and, more importantly, easily identifiable. This ensured that the morphodynamical character of the monitored solifluction processes would be similar and, thus, comparable. Morphometric analysis seemed to confirm this assumption, identifying a *typical* lobe form in all three study areas which had a tread angle of 21.2° ± 8.1°, a riser height of 0.41 m ± 0.16 m, a tread length of 2.56 m ± 1.89 m and a tread width of 3.88 m ± 2.19 m. A spatial inventory revealed that the majority of lobes (86.2%) were found on moderate alpine tundra slopes (18.8° ± 6.8°) located within a very narrow altitudinal belt (approximately 200 m in width) immediately above the local treeline. Further, it was discovered that, almost without exception, the study lobes were composed of a highly frost susceptible silty to stony loam having low liquid limits and limited plasticity.

The study had a fair measure of success in fulfilling its objectives. The data collected offers considerable insight into the contemporaneous and historical operation of solifluction within the Alberta Rocky Mountains region. For instance, it was established, for the first time, that solifluction is an active geomorphological agent within this region. The process data demonstrated that solifluction movements in this area ranged from zero to 2.50 cm/year at the ground surface. Examination of the associated subsurface velocity profiles indicated that this downslope motion decreased sharply with depth. In fact, at most of the sites, solifluction was confined to the uppermost 30 to 35 cm of sediment. Where deeper solifluction was indicated, it resulted in the transport of up to 59.61 cm^3/cm of sediment on an annual basis.

Overall, the mean rates and magnitudes of solifluction varied only slightly, and insignificantly, within the field area over the study period. Displacements measured at the different study sites proved to be similar to those recorded throughout the entire field area. Similarly, there was little suggestion of any significant temporal variability within these displacements from one measurement period to the next. The mean rate of contemporary solifluction transport established by these field studies was 0.62 cm/year, with a standard deviation ranging from 0.40 to 0.82 cm/year. Estimates of the amount of sediment transported by this activity suggested that an average of 8.67 ± 3.57 cm^3/cm /year of sediment was moved at each of the monitored lobe sites. These rates and magnitudes of solifluction are low relative to much of the previously published data. However, the fact that such a large pool of data was used to describe solifluction activity within this area, means that a more characteristic description of the average rate of solifluction was achieved than was possible in many of the preceding studies.

It was also shown that the rates of solifluction recorded were essentially proportional to the gradient of the slope on which they occurred. Further, it was shown that solifluction processes were intensified on north- to northeast-facing slopes, where the highest rates of surface displacement were observed. This evidence served to substantiate the significant role played by location and suggested that the rate of solifluction, like the operation of many other slope processes within high mountain settings (c.f. Gardner, 1983b; Caine, 1984), is highly dependent upon its spatial setting.

Solifluction rates within the field area were not shown to vary significantly with regards to differing sedimentological characteristics. An evaluation of the effect climate had on the measured rates of solifluction disclosed that there was little evidence to suggest that areal variations in the periglacial climates experienced by the three study areas were responsible for differentially influencing solifluction activity. On the other hand, microclimatic investigations completed in the Mt.Rae study area demonstrated how seasonal soil moisture and temperature fluctuations induced slight temporal variations in the local rates of solifluction. Investigations designed specifically to evaluate the relationships between the magnitude of solifluction activity and the vegetation cover of the study lobes provided inconclusive results. Specifically, they did not indicate whether or not solifluction movements were affected by or influenced the covering mantle of vegetation at these turf-banked solifluction lobe sites.

Despite the fact that the measured rates of solifluction were shown not to have varied significantly within the field area, observations at several of the study lobes demonstrated that differential movements were commonplace. Specifically, these observations indicated that the most rapid rates of transport occurred along the lobe axis, while only limited motion occurred near the lobe front and surrounding perimeter. This concentration of rapid solifluction movement, along linear pathways behind relatively stable risers, accords with previous observations. Its significance, in the present context, arises because only a relatively small percentage of the lobes examined are actively advancing at the present time. Instead, most appear to be in a state of relative quiescence, with present upslope additions of sediment being incorporated behind largely immobile perimeters.

Taken in conjunction with the measurements of frost heave made concurrently at two sites in the Mt.Rae area (1980-1983), these spatial patterns of solifluction were used to distinguish the contributions made by the different solifluction mechanisms. On the basis of these observations, it is suggested that where gelifluction mechanisms predominate, they result in sediment transport rates which, at a minimum, are an order of magnitude greater than the average rates of solifluction recorded by this study. However, because gelifluction dominated movements were distinguished at relatively few of the lobe plots, it is suggested that frost creep mechanisms provided the largest downslope component of solifluction within the field area. Clearly, though, while these observations did provide some circumstantial evidence of the relative contributions made by frost creep and gelifluction mechanisms to solifluction, the differential influences of retrograde movements masked much of the evidence needed to substantiate these findings.

Radiocarbon dating of organic horizons buried by two solifluction lobes in the Mt.Rae study area provided the first record of past solifluction in the Alberta Rocky Mountains. After being corrected to account for their C^{14} age at the time of burial, these radiocarbon dates were used to establish an absolute chronology of the average rate of frontal advance at the two lobe sites. A series of radiocarbon dates from beneath one of the lobes indicated that it had moved 9 m at an average rate of 0.49 cm/year during the last 4000 years. However, this radiocarbon record suggested that there were large temporal fluctuations in the rate of this activity, ranging from about 0.13 cm/year in one interval to about 0.89 cm/year in another. A comparison with what was known about the paleoclimate at this site suggested that these changes in the rate of frontal advance are a reflection of climatic fluctuations. At the second lobe site, where the lobe front advanced about 4 m in 1300 years, the radiocarbon evidence was less precise because only three dates were obtained. Apparently, the front of this lobe advanced downslope at an average rate of 0.29 cm/year throughout the record. There was some indication at this site that slower than average movements have occurred within the last century or so. These two radiocarbon records demonstrate that solifluction processes were continuously active at this particular study site for at least the last 4000 years. However, to what extent the historical rates of activity established at this site, relate to historical solifluction activity within the rest of the field area, awaits further study.

The results of this research program bear witness to the contemporary geomorphic significance of solifluction activity within the Alberta Rocky Mountains. The evidence collected firmly establishes that solifluction mass wasting is a highly active slope process in this mountain landscape at the present time. Even though its morphological effects are, at best, only subtly manifest, the magnitude of the sediment fluxes, described by its year to year operation, represent a level of geomorphic work which ranks closely in importance to many other slope processes active in this high mountain setting.

Despite the limitations inherent to these relatively short-term records of contemporary solifluction activity, it is anticipated that the results of these field investigations will increase the attention paid to slow mass wasting processes in the western Canadian cordillera. Ultimately, this increased interest will enable future surveys of alpine processes within this region to better appreciate the geomorphic role of solifluction than was possible in the past (c.f. Slaymaker, 1974, 1977; Slaymaker and McPherson, 1977). In the end, this increased sensitivity to the geomorphic significance of solifluction will provide a clearer perspective on geomorphic change in this midlatitude high mountain setting.

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APPENDICES

Appendix I : Inclinometer Tube Measurements

ANNUAL MEASUREMENTS OF INCLINOMETER TUBES
(values cm/year)

LOBE 1

depth cm	1980 1981	1981 1982	1982 1983
2	0.50	0.00	
4	0.50	0.00	
6	0.50	0.00	
8	0.40	0.00	
10	0.40	0.10	
12	0.40	0.10	
14	0.35	0.10	
16	0.30	0.15	
18	0.25	0.20	
20	0.20	0.30	
22	0.10	0.30	
24	0.10	0.35	
26	0.05	0.40	
28	0.00	0.50	
30		0.50	
32		0.50	
34		0.50	
36		0.45	
38		0.35	
40		0.25	
42		0.15	
44		0.05	
46		0.00	
95	0.00	0.00	

LOBE 4

depth (cm)	1980 1981	1981 1982	1982 1983
2		0.75	1.25
4		0.60	1.20
6		0.50	1.20
8		0.40	1.20
10		0.25	1.20
12		0.15	1.15
14		0.05	1.40
16		0.00	1.35
18			1.15
20			1.05
22			0.80
24			0.65
26			0.50
28			0.25
30			0.10
32			0.00
81		0.00	0.00

LOBE 5

depth (cm)	1980 1981	1981 1982	1982 1983
2		0.55	0.50
4		0.50	0.40
6		0.50	0.40
8		0.40	0.35
10		0.60	0.40
12		0.25	0.35
14		0.20	0.25
16		0.20	0.30
18		0.25	0.20
20		0.20	0.25
22		0.15	0.05
24		0.25	0.00
26		0.20	
28		0.10	
30		0.05	
32		0.00	
105		0.00	0.00

LOBE 6

depth (cm)	1980 1981	1981 1982	1982 1983
2	0.55	0.55	0.90
4	0.52	0.52	0.85
6	0.45	0.45	0.85
8	0.40	0.40	0.80
10	0.30	0.30	0.78
12	0.22	0.22	0.65
14	0.18	0.18	0.60
16	0.11	0.11	0.60
18	0.08	0.08	0.50
20	0.00	0.00	0.40
22			0.40
24			0.30
26			0.18
28			0.00
96	0.00	0.00	0.00

LOBE 7

depth (cm)	1980 1981	1981 1982	1982 1983
2	0.45	0.45	0.85
4	0.32	0.32	0.80
6	0.31	0.31	0.80
8	0.26	0.26	0.70
10	0.25	0.25	0.60
12	0.22	0.22	0.45
14	0.14	0.14	0.35
16	0.12	0.12	0.25
18	0.07	0.07	0.30
20	0.02	0.02	0.30
22	0.00	0.00	0.22
24			0.20
26			0.10
28			0.10
30			0.10
32			0.10
34			0.10
36			0.10
38			0.10
40			0.05
42			0.00
86	0.00	0.00	0.00

LOBE 10

depth (cm)	1980 1981	1981 1982	1982 1983
2	1.90	0.85	0.25
4	1.65	0.80	0.20
6	1.50	0.75	0.20
8	1.25	0.60	0.25
10	1.10	0.60	0.30
12	0.90	0.50	0.30
14	0.80	0.40	0.40
16	0.65	0.35	0.50
18	0.58	0.30	0.50
20	0.45	0.30	0.50
22	0.40	0.30	0.50
24	0.40	0.22	0.40
26	0.40	0.20	0.40
28	0.40	0.20	0.40
30	0.40	0.20	0.40
32	0.40	0.21	0.35
34	0.40	0.25	0.30
36	0.35	0.30	0.20
38	0.25	0.30	0.00
40	0.15	0.35	
42	0.05	0.40	
44	0.00	0.40	
46		0.30	
48		0.20	
50		0.10	
52		0.00	
88	0.00	0.00	0.00

LOBE 11

depth (cm)	1980 1981	1981 1982	1982 1983
2	0.55	0.30	0.40
4	0.50	0.30	0.30
6	0.45	0.20	0.20
8	0.40	0.17	0.05
10	0.38	0.00	0.00
12	0.35		
14	0.20		
16	0.05		
18	0.00		
75	0.00	0.00	0.00

LOBE 12

depth (cm)	1980 1981	1981 1982	1982 1983
2	0.75	0.50	0.90
4	0.65	0.40	0.70
6	0.60	0.40	0.60
8	0.50	0.40	0.40
10	0.35	0.40	0.30
12	0.20	0.35	0.20
14	0.05	0.30	0.15
16	0.00	0.30	0.10
18		0.25	0.00
20		0.20	
22		0.15	
24		0.05	
26		0.00	
86	0.00	0.00	0.00

LOBE 13

depth	1980	1981	1982
(cm)	1981	1982	1983
2	1.00	1.40	0.45
4	0.90	1.20	0.40
6	0.80	1.10	0.40
8	0.75	0.98	0.40
10	0.60	0.80	0.40
12	0.40	0.78	0.40
14	0.25	0.60	0.40
16	0.15	0.58	0.35
18	0.05	0.45	0.30
20	0.00	0.40	0.30
22		0.30	0.30
24		0.20	0.20
26		0.20	0.20
28		0.10	0.10
30		0.05	0.05
32		0.00	0.00
69	0.00	0.00	0.00

LOBE 22

depth	1980	1981	1982
(cm)	1981	1982	1983
2	0.90	1.10	
4	0.75	1.15	
6	0.50	1.15	
8	0.40	1.15	
10	0.35	1.10	
12	0.25	0.90	
14	0.20	0.80	
16	0.18	0.70	
18	0.10	0.50	
20	0.00	0.40	
22		0.40	
24		0.35	
26		0.28	
28		0.10	
30		0.00	
80	0.00	0.00	

LOBE 14

depth	1980	1981	1982
(cm)	1981	1982	1983
2	1.00	0.60	
4	1.00	0.50	
6	1.00	0.40	
8	0.90	0.30	
10	0.80	0.20	
12	0.75	0.10	
14	0.70	0.05	
16	0.55	0.00	
18	0.50		
20	0.40		
22	0.28		
24	0.10		
26	0.00		
87	0.00	0.00	

LOBE 24

depth	1980	1981	1982
(cm)	1981	1982	1983
2	0.00		
4	0.00		
6	0.00		
8	0.00		
10	0.10		
12	0.22		
14	0.35		
16	0.40		
18	0.45		
20	0.55		
22	0.60		
24	0.60		
26	0.55		
28	0.45		
30	0.35		
32	0.30		
34	0.20		
36	0.15		
38	0.10		
40	0.05		
42	0.00		
100	0.00		

LOBE 25

depth (cm)	1980 1981	1981 1982	1982 1983
2	0.50		
4	0.50		
6	0.50		
8	0.50		
10	0.50		
12	0.50		
14	0.50		
16	0.50		
18	0.50		
20	0.30		
22	0.20		
24	0.00		
100	0.00		

LOBE 26

depth (cm)	1980 1981	1981 1982	1982 1983
2	0.70	0.65	
4	0.75	0.60	
6	0.80	0.60	
8	0.80	0.65	
10	0.90	0.60	
12	0.90	0.60	
14	0.95	0.60	
16	0.90	0.60	
18	0.90	0.45	
20	0.90	0.30	
22	0.85	0.22	
24	0.82	0.20	
26	0.75	0.20	
28	0.60	0.20	
30	0.40	0.20	
32	0.25	0.15	
34	0.10	0.10	
36	0.00	0.00	
95	0.00	0.00	

LOBE 28

depth (cm)	1980 1981	1981 1982	1982 1983
2		0.30	
4		0.20	
6		0.05	
8		0.00	
54		0.00	

LOBE 29

depth (cm)	1980 1981	1981 1982	1982 1983
2	1.80	0.90	
4	1.60	0.85	
6	1.50	0.75	
8	1.20	0.75	
10	0.90	0.75	
12	0.70	0.75	
14	0.50	0.75	
16	0.38	0.60	
18	0.20	0.50	
20	0.10	0.40	
22	0.00	0.25	
24		0.10	
26		0.00	
83	0.00	0.00	

LOBE 30

depth (cm)	1980 1981	1981 1982	1982 1983
2			2.00
4			1.75
6			1.60
8			1.55
10			1.40
12			1.20
14			1.00
16			0.80
18			0.70
20			0.50
22			0.40
24			0.30
26			0.20
28			0.10
30			0.00
89			0.00

LOBE 31

depth (cm)	1980 1981	1981 1982	1982 1983
2	1.10	1.10	0.75
4	1.00	1.00	0.70
6	0.90	0.90	0.75
8	0.75	0.75	0.72
10	0.70	0.70	0.60
12	0.55	0.55	0.57
14	0.50	0.50	0.55
16	0.40	0.40	0.40
18	0.35	0.35	0.30
20	0.31	0.31	0.20
22	0.30	0.30	0.05
24	0.25	0.25	0.00
26	0.22	0.22	
28	0.20	0.20	
30	0.17	0.17	
32	0.12	0.12	
34	0.05	0.05	
36	0.00	0.00	
102	0.00	0.00	0.00

LOBE 32

depth (cm)	1980 1981	1981 1982	1982 1983
2	0.70	0.70	1.50
4	0.70	0.70	1.30
6	0.70	0.70	1.00
8	0.70	0.70	0.80
10	0.70	0.70	0.68
12	0.70	0.70	0.50
14	0.75	0.75	0.30
16	0.75	0.75	0.15
18	0.75	0.75	0.00
20	0.70	0.70	
22	0.70	0.70	
24	0.62	0.62	
26	0.55	0.55	
28	0.50	0.50	
30	0.40	0.40	
32	0.30	0.30	
34	0.20	0.20	
36	0.10	0.10	
38	0.05	0.05	
40	0.00	0.00	
90	0.00	0.00	0.00

LOBE 33

depth (cm)	1980 1981	1981 1982	1982 1983
2	1.00	1.00	0.80
4	1.05	1.05	0.65
6	1.05	1.05	0.50
8	1.05	1.05	0.40
10	1.10	1.10	0.30
12	1.10	1.10	0.25
14	1.10	1.10	0.15
16	1.10	1.10	0.05
18	1.10	1.10	0.00
20	1.05	1.05	
22	1.00	1.00	
24	0.95	0.95	
26	0.90	0.90	
28	0.80	0.80	
30	0.80	0.80	
32	0.60	0.60	
34	0.55	0.55	
36	0.50	0.50	
38	0.40	0.40	
40	0.37	0.37	
42	0.22	0.22	
44	0.20	0.20	
46	0.10	0.10	
48	0.00	0.00	
87	0.00	0.00	0.00

LOBE 34

depth (cm)	1980 1981	1981 1982	1982 1983
2	0.80	0.87	0.87
4	0.78	0.75	0.75
6	0.60	0.75	0.75
8	0.50	0.80	0.80
10	0.38	0.80	0.80
12	0.25	0.70	0.70
14	0.10	0.70	0.70
16	0.00	0.63	0.63
18		0.55	0.55
20		0.50	0.50
22		0.40	0.40
24		0.30	0.30
26		0.15	0.15
28		0.08	0.08
30		0.00	0.00
98	0.00	0.00	0.00

LOBE 35

depth (cm)	1980 1981	1981 1982	1982 1983
2	1.00	1.10	0.75
4	1.00	1.05	0.60
6	1.00	1.00	0.57
8	1.00	1.00	0.50
10	1.00	1.00	0.45
12	1.00	0.90	0.40
14	1.00	0.80	0.40
16	1.00	0.60	0.40
18	1.00	0.50	0.40
20	1.00	0.40	0.40
22	1.00	0.25	0.40
24	0.90	0.10	0.40
26	0.80	0.00	0.40
28	0.60		0.40
30	0.50		0.10
32	0.35		0.00
34	0.20		
36	0.10		
38	0.00		
97	0.00	0.00	0.00

LOBE 36

depth (cm)	1980 1981	1981 1982	1982 1983
2	1.70	0.90	0.90
4	1.55	0.80	0.80
6	1.30	0.70	0.70
8	1.15	0.65	0.65
10	1.10	0.55	0.55
12	0.90	0.50	0.50
14	0.70	0.45	0.45
16	0.50	0.35	0.35
18	0.40	0.30	0.30
20	0.25	0.22	0.22
22	0.15	0.18	0.18
24	0.05	0.12	0.12
26	0.00	0.08	0.08
28		0.00	0.00
112	0.00	0.00	0.00

LOBE 37_1

depth (cm)	1980 1981	1981 1982	1982 1983
2	2.65	2.00	2.05
4	2.55	1.85	2.10
6	2.50	1.80	1.95
8	2.40	1.70	1.90
10	2.30	1.60	1.70
12	2.20	1.55	1.50
14	1.90	17.5	1.35
16	1.65	1.70	1.20
18	1.50	1.70	1.05
20	1.30	1.50	0.95
22	1.20	1.45	0.80
24	1.05	1.30	0.75
26	0.90	1.20	0.65
28	0.80	1.05	0.70
30	0.80	0.80	0.70
32	0.80	0.70	0.65
34	0.80	0.65	0.55
36	0.70	0.65	0.45
38	0.70	0.65	0.35
40	0.75	0.60	0.35
42	0.85	0.50	0.10
44	1.00	0.35	0.15
46	1.10	0.25	0.10
48	1.20	0.15	0.05
50	1.05	0.05	0.10
52	0.85	0.00	0.00
54	0.65	0.05	
56	0.50	0.00	
58	0.30	0.05	
60	0.15	0.05	
62	0.05	0.05	
64	0.00	0.05	
66		0.00	
97	0.00	0.00	0.00

LOBE 37_2

depth (cm)	1980 1981	1981 1982	1982 1983
2	0.90	0.30	0.30
4	0.70	0.30	0.30
6	0.60	0.27	0.27
8	0.40	0.25	0.25
10	0.40	0.20	0.20
12	0.25	0.12	0.12
14	0.20	0.12	0.12
16	0.10	0.10	0.10
18	0.05	0.05	0.05
20	0.00	0.00	0.00
112	0.00	0.00	0.00

LOBE 37_3

depth (cm)	1980 1981	1981 1982	1982 1983
2	0.65	0.70	0.20
4	0.60	0.65	0.20
6	0.60	0.50	0.15
8	0.60	0.40	0.05
10	0.50	0.25	0.00
12	0.45	0.15	
14	0.40	0.00	
16	0.20		
18	0.10		
20	0.00		
60	0.00	0.00	0.00

LOBE 38

depth (cm)	1980 1981	1981 1982	1982 1983
2	2.10	1.40	1.40
4	2.07	1.30	1.30
6	2.05	1.10	1.10
8	2.00	1.00	1.00
10	2.00	0.90	0.90
12	2.00	0.75	0.75
14	1.95	0.60	0.60
16	1.90	0.45	0.45
18	1.80	0.37	0.37
20	1.75	0.27	0.27
22	1.60	0.20	0.20
24	1.45	0.15	0.15
26	1.35	0.10	0.10
28	1.20	0.07	0.07
30	1.10	0.05	0.05
32	1.05	0.05	0.05
34	0.98	0.00	0.00
36	0.90		
38	0.80		
40	0.70		
42	0.60		
44	0.50		
46	0.40		
48	0.25		
50	0.10		
52	0.00		
112	0.00	0.00	0.00

LOBE 41

depth (cm)	1980 1981	1981 1982	1982 1983
2		0.10	0.10
4		0.12	0.12
6		0.15	0.15
8		0.12	0.12
10		0.10	0.10
12		0.10	0.10
14		0.07	0.07
16		0.01	0.01
18		0.00	0.00
76		0.00	0.00

LOBE 42

depth (cm)	1980 1981	1981 1982	1982 1983
2	1.50	0.50	0.50
4	1.30	0.45	0.50
6	1.20	0.45	0.55
8	0.95	0.55	0.25
10	0.70	0.55	0.35
12	0.55	0.50	0.35
14	0.40	0.40	0.25
16	0.25	0.35	0.15
18	0.10	0.50	0.10
20	0.00	0.35	0.10
22		0.20	0.10
24		0.05	0.10
26		0.00	0.05
28			0.00
74	0.00	0.00	0.00

LOBE 43

depth (cm)	1980 1981	1981 1982	1982 1983
2	0.40	0.60	
4	0.40	0.40	
6	0.40	0.25	
8	0.30	0.10	
10	0.25	0.05	
12	0.25	0.00	
14	0.20		
16	0.10		
18	0.00		
79	0.00	0.00	

LOBE 44

depth (cm)	1980 1981	1981 1982	1982 1983
2		0.55	0.55
4		0.50	0.50
6		0.35	0.40
8		0.30	0.35
10		0.20	0.30
12		0.15	0.25
14		0.05	0.10
16		0.00	0.05
18			0.00
84		0.00	0.00

LOBE 45

depth (cm)	1980 1981	1981 1982	1982 1983
2	0.47	0.47	0.47
4	0.42	0.42	0.42
6	0.35	0.35	0.35
8	0.28	0.28	0.28
10	0.20	0.20	0.20
12	0.13	0.13	0.13
14	0.07	0.07	0.07
16	0.03	0.03	0.03
18	0.00	0.00	0.00
76	0.00	0.00	0.00

LOBE 46

depth (cm)	1980 1981	1981 1982	1982 1983
2	1.40		
4	1.30		
6	1.20		
8	1.05		
10	0.90		
12	0.80		
14	0.65		
16	0.50		
18	0.40		
20	0.30		
22	0.20		
24	0.05		
26	0.00		
101	0.00		

LOBE 47

depth (cm)	1980 1981	1981 1982	1982 1983
2		0.07	0.07
4		0.05	0.05
6		0.02	0.02
8		0.02	0.02
10		0.02	0.02
12		0.10	0.10
14		0.12	0.12
16		0.15	0.15
18		0.20	0.20
20		0.22	0.22
22		0.25	0.25
24		0.20	0.20
26		0.20	0.20
28		0.15	0.15
30		0.10	0.10
32		0.05	0.05
34		0.02	0.02
36		0.00	0.00
98		0.00	0.00

LOBE 50_1

depth (cm)	1980 1981	1981 1982	1982 1983
2		1.00	0.15
4		1.00	0.25
6		1.00	0.35
8		0.90	0.35
10		0.80	0.40
12		0.50	0.60
14		0.45	0.55
16		0.25	0.70
18		0.15	0.60
20		0.05	0.75
22		0.00	0.80
24			0.80
26			0.80
28			0.80
30			0.80
32			0.80
34			0.80
36			0.75
38			0.75
40			0.75
42			0.75
44			0.75
46			0.70
48			0.65
50			0.65
52			0.55
54			0.45
56			0.25
58			0.20
60			0.15
62			0.05
64			0.00
109		0.00	0.00

LOBE 50,

depth (cm)	1980 1981	1981 1982	1982 1983
2		0.45	1.45
4		0.30	1.35
6		0.35	1.25
8		0.40	1.20
10		0.40	1.20
12		0.40	1.10
14		0.40	1.05
16		0.40	1.00
18		0.30	1.00
20		0.22	1.00
22		0.20	1.10
24		0.15	1.15
26		0.10	1.20
28		0.10	1.10
30		0.15	1.10
32		0.20	1.00
34		0.20	1.00
36		0.20	0.90
38		0.20	0.77
40		0.20	0.60
42		0.20	0.60
44		0.20	0.45
46		0.20	0.45
48		0.18	0.45
50		0.10	0.50
52		0.00	0.42
54			0.35
56			0.10
58			0.00
99		0.00	0.00

LOBE 50.

depth (cm)	1980 1981	1981 1982	1982 1983
2		1.35	0.20
4		1.30	0.20
6		1.20	0.20
8		1.10	0.25
10		0.90	0.25
12		0.80	0.25
14		0.70	0.30
16		0.60	0.25
18		0.50	0.20
20		0.40	0.20
22		0.42	0.00
24		0.45	
26		0.40	
28		0.40	
30		0.30	
32		0.20	
34		0.10	
36		0.00	
107		0.00	0.00

LOBE 50,

depth (cm)	1980 1981	1981 1982	1982 1983
2		0.60	1.75
4		0.60	1.60
6		0.60	1.25
8		0.60	1.10
10		0.60	0.90
12		0.60	0.80
14		0.60	0.60
16		0.60	0.45
18		0.60	0.35
20		0.50	0.25
22		0.50	0.21
24		0.50	0.20
26		0.50	0.20
28		0.50	0.10
30		0.50	0.05
32		0.05	0.00
34		0.05	0.00
36		0.05	0.00
38		0.05	0.00
40		0.45	0.00
42		0.37	0.18
44		0.25	0.20
46		0.20	0.25
48		0.10	0.30
50		0.00	0.40
52			0.30
54			0.20
56			0.05
58			0.00
108		0.00	0.00

LOBE 51.

depth (cm)	1980 1981	1981 1982	1982 1983
2		0.20	2.20
4		0.20	1.80
6		0.25	1.30
8		0.30	1.00
10		0.30	0.75
12		0.30	0.50
14		0.30	0.40
16		0.30	0.30
18		0.30	0.20
20		0.30	0.20
22		0.20	0.10
24		0.30	0.00
26		0.40	
28		0.30	
30		0.25	
32		0.25	
34		0.30	
36		0.40	
38		0.45	
40		0.50	
42		0.50	
44		0.50	
46		0.50	
48		0.50	
50		0.40	
52		0.30	
54		0.20	
56		0.00	
104		0.00	0.00

LOBE 52

depth (cm)	1980 1981	1981 1982	1982 1983
2		0.80	0.75
4		0.75	0.60
6		0.65	0.50
8		0.55	0.38
10		0.50	0.20
12		0.40	0.10
14		0.40	0.05
16		0.30	0.00
18		0.20	
20		0.15	
22		0.05	
24		0.00	
107		0.00	0.00

LOBE 53

depth (cm)	1980 1981	1981 1982	1982 1983
2		0.95	0.95
4		0.90	0.90
6		0.90	0.90
8		0.86	0.86
10		0.80	0.80
12		0.80	0.80
14		0.72	0.72
16		0.70	0.70
18		0.63	0.63
20		0.60	0.60
22		0.55	0.55
24		0.50	0.50
26		0.35	0.35
28		0.30	0.30
30		0.20	0.20
32		0.10	0.10
34		0.09	0.09
36		0.05	0.05
38		0.00	0.00
100		0.00	0.00

LOBE 54

depth (cm)	1980 1981	1981 1982	1982 1983
2		0.15	0.15
4		0.15	0.15
6		0.15	0.15
8		0.15	0.15
10		0.15	0.15
12		0.15	0.15
14		0.15	0.15
16		0.15	0.15
18		0.15	0.15
20		0.15	0.15
22		0.10	0.10
24		0.10	0.10
26		0.08	0.08
28		0.04	0.04
30		0.00	0.00
107		0.00	0.00

LOBE 55

depth (cm)	1980 1981	1981 1982	1982 1983
2		0.75	0.75
4		0.70	0.70
6		0.68	0.68
8		0.63	0.63
10		0.55	0.55
12		0.52	0.52
14		0.50	0.50
16		0.45	0.45
18		0.38	0.38
20		0.37	0.37
22		0.30	0.30
24		0.25	0.25
26		0.25	0.25
28		0.25	0.25
30		0.25	0.25
32		0.25	0.25
34		0.22	0.22
36		0.20	0.20
38		0.18	0.18
40		0.11	0.11
42		0.07	0.07
44		0.01	0.01
46		0.00	0.00
112		0.00	0.00

LOBE 60

depth (cm)	1980 1981	1981 1982	1982 1983
2		1.45	1.45
4		1.30	1.30
6		1.05	1.05
8		0.90	0.90
10		0.80	0.80
12		0.65	0.65
14		0.55	0.55
16		0.44	0.44
18		0.35	0.35
20		0.32	0.32
22		0.28	0.28
24		0.22	0.22
26		0.20	0.20
28		0.20	0.20
30		0.20	0.20
32		0.20	0.20
34		0.22	0.22
36		0.25	0.25
38		0.26	0.26
40		0.30	0.30
42		0.30	0.30
44		0.30	0.30
46		0.30	0.30
48		0.28	0.28
50		0.27	0.27
52		0.22	0.22
54		0.18	0.18
56		0.05	0.05
58		0.02	0.02
60		0.00	0.00
92		0.00	0.00

LOBE 62_1

depth (cm)	1980 1981	1981 1982	1982 1983
2		0.40	0.90
4		0.40	0.60
6		0.30	0.50
8		0.25	0.45
10		0.21	0.40
12		0.18	0.30
14		0.00	0.27
16			0.20
18			0.10
20			0.00
92		0.00	0.00

LOBE 62_2

depth (cm)	1980 1981	1981 1982	1982 1983
2		0.50	0.50
4		0.52	0.52
6		0.53	0.53
8		0.50	0.50
10		0.50	0.50
12		0.50	0.50
14		0.45	0.45
16		0.40	0.40
18		0.35	0.35
20		0.32	0.32
22		0.32	0.32
24		0.30	0.30
26		0.29	0.29
28		0.30	0.30
30		0.30	0.30
32		0.30	0.30
34		0.30	0.30
36		0.30	0.30
38		0.32	0.32
40		0.38	0.38
42		0.35	0.35
44		0.30	0.30
46		0.30	0.30
48		0.25	0.25
50		0.20	0.20
52		0.18	0.18
54		0.11	0.11
56		0.10	0.10
58		0.05	0.05
60		0.01	0.01
62		0.00	0.00
65		0.00	0.00

Appendix II : Dowelling Pillar Measurements

DOWELLING PILLAR MEASUREMENTS
(values cm/year)

LOBE 3
1977
1981

depth (cm)	cm/year
2	0.50
4	0.50
6	0.50
8	0.50
10	0.45
12	0.43
14	0.38
16	0.35
18	0.31
20	0.26
22	0.25
24	0.25
26	0.26
28	0.25
30	0.23
32	0.20
34	0.13
36	0.13
38	0.08
40	0.03
42	0.03
44	0.00
70	0.00

LOBE 10
1977
1982

depth (cm)	cm/year
2	0.78
4	0.78
6	0.78
8	0.78
10	0.78
12	0.78
14	0.70
16	0.62
18	0.45
20	0.41
22	0.35
24	0.30
26	0.24
28	0.15
30	0.15
32	0.10
34	0.06
36	0.05
38	0.04
40	0.02
42	0.00
52	0.00

LOBE 13
1980
1982

depth (cm)	cm/year
2	1.08
4	0.90
6	0.73
8	0.58
10	0.55
12	0.53
14	0.49
16	0.38
18	0.30
20	0.28
22	0.25
24	0.18
26	0.05
28	0.02
30	0.00
40	0.00

LOBE 14
1980
1982

depth (cm)	cm/year
2	1.00
4	1.00
6	1.00
8	0.95
10	0.95
12	0.93
14	0.88
16	0.75
18	0.68
20	0.55
22	0.35
24	0.17
26	0.05
28	0.01
39	0.00
53	0.00

LOBE 23
1980
1982

depth (cm)	cm/year
2	0.65
4	0.50
6	0.50
8	0.45
10	0.45
12	0.50
14	0.50
16	0.50
18	0.48
20	0.38
22	0.28
24	0.23
26	0.08
28	0.00
50	0.00

LOBE 25
1980
1982

depth (cm)	cm/year
2	0.37
4	0.30
6	0.23
8	0.13
10	0.08
12	0.05
14	0.02
16	0.00
53	0.00

LOBE 33
1980
1982

depth (cm)	cm/year
2	0.63
4	0.55
6	0.65
8	0.70
10	0.70
12	0.55
14	0.45
16	0.25
18	0.20
20	0.15
22	0.15
24	0.15
26	0.10
28	0.05
30	0.00
76	0.00

LOBE 35
1980
1982

depth (cm)	cm/year
2	0.70
4	0.55
6	0.50
8	0.40
10	0.40
12	0.43
14	0.50
16	0.40
18	0.45
20	0.50
22	0.45
24	0.40
26	0.40
28	0.40
30	0.40
32	0.40
34	0.40
36	0.40
38	0.45
40	0.30
42	0.10
44	0.00
50	0.00

LOBE 37A
1980
1982

depth (cm)	cm/year
2	2.00
4	2.10
6	2.20
8	2.20
10	2.20
12	2.15
14	2.15
16	1.85
18	1.70
20	1.30
22	1.20
24	1.00
26	0.75
28	0.50
30	0.40
32	0.35
34	0.25
36	0.20
38	0.20
40	0.00
58	0.00

LOBE 38
1980
1982

depth (cm)	cm/year
2	0.75
4	0.50
6	0.50
8	0.63
10	0.90
12	0.95
14	0.95
16	1.20
18	1.38
20	1.50
22	1.40
24	1.10
26	0.50
28	0.50
30	0.00
73	

Appendix III : Painted Stone Measurements

PAINTED STONE MEASUREMENTS
(values cm/year)

LOBE 10

#	1980 1981	1981 1982	1982 1983
1	0.00	0.00	0.00
2	0.00	0.00	0.20
3	0.35	0.35	0.80
4	0.10	0.10	0.20
5	0.20	0.20	0.30
6	0.65	0.65	0.00
7	0.00	0.00	0.10
8	0.95	0.95	lost
9	0.80	0.80	0.00
10	0.75	0.75	lost
11	0.50	0.50	0.20
12	lost	lost	lost
13	0.25	0.25	0.00
14	0.25	0.25	0.20
15	1.25	1.25	0.70
16	1.45	1.45	0.90
17	lost	lost	lost
18	0.55	0.55	lost
mean	0.50	0.50	0.28

LOBE 11A

#	1980 1981	1981 1982	1982 1983
1	0.35	0.35	0.00
2	0.60	0.60	0.20
3	0.60	0.60	0.00
4	0.55	0.55	0.00
5	0.50	0.50	0.00
6	0.13	0.13	0.13
7	0.85	0.85	0.30
8	0.55	0.55	0.00
9	0.80	0.80	lost
10	0.65	0.65	lost
11	0.80	0.80	0.20
mean	0.58	0.58	0.09

LOBE 11B

#	1980 1981	1981 1982	1982 1983
1	0.00	0.00	
2	0.00	0.00	
3	0.00	0.00	
4	0.00	0.00	
5	0.10	0.10	
6	0.70	0.70	
7	lost	lost	
8	0.25	0.25	
9	0.55	0.55	
10	0.25	0.25	
11	lost	lost	
12	0.08	0.08	
13	0.00	0.00	
mean	0.17	0.17	

LOBE 13A

#	1980 1981	1981 1982	1982 1983
1	0.20	0.20	0.00
2	0.75	0.75	1.00
3	0.05	0.05	0.30
4	0.75	0.75	0.40
5	1.10	1.10	0.80
6	0.75	0.75	0.00
7	1.10	1.10	0.80
8	0.75	0.75	0.50
9	0.60	0.60	0.10
10	0.95	0.95	1.60
11	0.95	0.95	0.30
12	0.55	0.55	1.00
13	0.85	0.85	1.10
14	1.15	1.15	1.10
15	0.85	0.85	0.50
16	0.43	0.43	0.43
17	0.00	0.00	lost
18	0.25	0.25	0.20
19	1.00	1.00	0.00
20	lost	lost	lost
mean	0.71	0.71	0.52

LOBE 13B

#	1980 1981	1981 1982	1982 1983
1	0.80	0.80	
2	0.90	0.90	
3	1.30	1.30	
4	1.90		1.90
5	0.60		0.60
6	0.70		0.70
7	0.00		0.00
8	0.60		0.60
9	0.40		0.40
10	0.60		0.60
11	1.00	1.00	
12	0.10	0.10	
13	1.20	1.20	
14	1.00	1.00	
15	0.60	0.60	
16	1.80	1.80	
17	1.40	1.40	
mean	0.44	0.44	

LOBE 14

#	1980 1981	1981 1982	1982 1983
1	0.40	0.40	lost
2	0.15	0.15	0.20
3	0.95	0.95	1.90
4	2.60	2.60	1.40
5	lost	lost	lost
6	1.30	1.30	1.70
mean	1.08	1.08	1.30

LOBE 21

#	1980 1981	1981 1982	1982 1983
1	0.40	0.00	0.00
2	0.40	0.30	0.10
3	1.00	0.30	0.30
4	0.80	0.40	0.00
5	0.00	0.00	0.20
6	0.30	0.20	0.00
7	0.30	0.30	0.30
8	0.40	0.20	0.00
9	0.50	lost	lost
10	0.80	0.40	0.00
21	0.10	0.40	0.00
mean	0.36	0.25	0.09

LOBE 23

#	1980 1981	1981 1982	1982 1983
1	lost	lost	
2	lost	lost	
3	0.60	0.60	
4	1.20	0.70	
5	0.30	0.10	
6	1.00	0.20	
7	1.40	0.40	
8	0.40	0.00	
9	0.00	0.00	
10	0.00	0.00	
11	0.10	0.00	
12	0.00	0.00	
13	0.30	0.00	
mean	0.65	0.65	

LOBE 41A

#	1980 1981	1981 1982	1982 1983
1	lost	lost	
2	0.30	0.30	
3	0.10	0.10	
4	0.00	0.00	
5	lost	lost	
6	0.30	0.30	
7	lost	lost	
8	1.30	1.30	
9	0.70	0.70	
10	0.25	0.25	
11	0.35	0.35	
12	0.40	0.40	
13	0.25	0.25	
14	1.00	1.00	
15	0.65	0.65	
mean	0.54	0.54	

LOBE 41B

#	1980 1981	1981 1982	1982 1983
1	0.20	0.20	
2	lost	lost	
3	0.10	0.10	
4	0.15	0.15	
5	0.00	0.00	
6	0.00	0.00	
7	0.05	0.05	
8	0.10	0.10	
9	0.15	0.15	
10	0.40	0.40	
11	0.50	0.50	
12	0.30	0.30	
mean	0.17	0.17	

Appendix IV : Flora

SYSTEMATIC CHECKLIST OF VASCULAR PLANT TAXA ASSOCIATED WITH SOLIFLUCTION LOBES IN THE FIELD AREA

BORAGINACEA
Myosotis sylvatica var. ***alpestris*** (Schm.) Koch. f. ***alpestris***

CAROPHYLLACEA
Arenaria capillaris Poir. var. ***americana*** (Maguire) Davis
Cerasitum berringianum Cham. & Schlecht ssp. ***earlei*** (Rydb.) Hult.
Silene acaulis L.

COMPOSITAE
Achillea millefolium L.
Agoseris glauca (Pursh) Raf. var. ***dasycephala*** (T. & G.) Jeps.
Antennaria lanata (Hook.) Greene
Antennaria media Greene
Arnica mollis Hook.
Erigeron aureus Greene
Erigeron humilis Graham
Erigeron peregrinus (Pursh) Greene ssp. ***callianthemus*** (Greene) Cronq. var. ***scapsosus*** (T. & G.) Cronq.
Erigeron purpuratus Greene ssp. ***pallens*** (Cronq.) G. Douglas
Saussurea nuda Ledeb.
Senecio integerrimus Nutt. var. ***exaltus*** (Nutt.) Cronq.
Senecio triangularis Hook.
Solidago multiradiata Ait.
Taraxacum certaphorum (Ledeb.) DC.

CRASSULACEAE
Sedum lanceolatum Torr.
Tolmachevia integrifolia (Raf.) Love and Love

CRUCIFERAE
Arabis lyallii S. Watts
Draba fladnizensis Wulfen var. ***fladnizensis***
Draba oligosperma Hook.
Draba paysonii Macbr. var. ***treleasii*** (Schulz) Hitchc.
Smelowskia calycina (Stephan) C.A. Mey.

CYPERACEAE
Carex nigricans C.A. Meyer.
Carex phaeocephala Piper
Carex rupestris All.
Kobresia myosuroides (Vill.) Fiori & Paol.

EQUISETACEAE
Equisetum scirpoides Michx.

ERICACEAE
Cassiope tetragona (L.) D. Don
Phyllodoce aleutica (Spreng.) Heller ssp. ***glanduliflora*** (Hook.) Hult
Vaccimium scoparium Leiberg.

GENTIANACEAE
Gentianella propinqua (Richards) J.M. Gillett

GRAMINEAE
Festuca ovina L. var. ***brachyphylla*** (Schultes) Piper f. ***brachyphylla***
Phleum communtatum Gaudin
Poa alpina L.
Poa arctica R. Br.
Trisetum spicatum (L.) Richter var. ***maidenii*** (Gand.) Fern.
Vahlodea atropurpurea (Wahl.) Fries. ssp. ***latifolia*** (Hook.) Pors.

JUNCACEAE
Juncus drummondii E. Meyer

Luzula spicata (L.) DC.

LEGUMINOSAE
Astragalus alpinus L. var. *alpinus* f. *alpinus*
Hedysarum sulphurescens Rydb.
Oxytropis podocarpa A. Gray

LYCOPODIACEAE
Selaginella densa Rydb.

ONAGRACEAE
Epilobium angustifolium L.

PARNASSIACEAE
Parnassia fimbrata Koing.

PINACEAE
Larix lyallii Parl.

POLYGONACEAE
Oxyria digyma (L.) Hill
Polygonum viviparum L. f. *alpinum* (Wahl.) Polunin

PRIMULACEAE
Androsace septentrionalis L. var. *subumbellata* Nels.

RANUNCULACEAE
Anemone lithophila Rydb.
Anemone occidentalis S. Wats.
Anemone parviflora Michx.
Ranunculus eschscholtzi Schlecht var. *suksdorfii* (Gray) Benson
Ranunculus pygmaeus Wahl.
Trollis albiflorus (A. Gray) Rydb.
Trollis laxus Salisb.

ROSACEAE
Dryas octopetala L. ssp. *hookeriana* (Juz.) Hult.
Fragaria glauca (Wats.) Rydb.
Fragaria virginiana Duchesne ssp. *glauca* (S. Wats.) Staudt.
Potentilla diversifolia Lehm.
Potentilla hyparctica Multe var. *elatior* (Abrom) Fern.
Potentilla nivea L.
Sibbaldia procumbens L.

SALICACEAE
Salix arctica Pallas
Salix barrattiana Hook.
Salix reticulata L. ssp. *nivalis* Love

SCROPHULARIACEAE
Castilleja miniata Dougl.
Castilleja occidentalis Torr.
Pedicularis bracteosa Benth
Penstemon ssp.
Veronica alpina L.

SAXIFRAGACEAE
Saxifraga adscendens L. ssp. *oregonensis* (Raf.) Baciogalupi
Saxifraga cernua L.
Saxifraga lyallii Engler
Saxifraga oppositifolia L.
Saxifraga rhomboidea Greene

VALERIANACEA
Valeriana sitchensis Bong.

Appendix V : Distributional Character of Vegetation

DISTRIBUTIONAL CHARACTER OF PLANT SPECIES BY LOBE AND QUADRAT

species	QUADRAT (values are modified Braun Blanquet scale in Table 8.12) A	B	C
LOBE 1			
Achillia millefolium		1	+
Anemone drummondii		1	
Antennaria lanata			1
Antennaria media		1	1
Arnica mollis	3	2	
Carex nigricans		+	1
Draba fladnizensis		+	
Equisetum scriopoides			+
Erigeron aureus		1	
Erigeron peregrinus	1		+
Festuca ovina	+		
Fragaria virginana		1	
Gentianella propinquas			+
Juncus drummondii	3	1	
Luzula spicata	1	+	
Oxytropis podocarpa			+
Phyllodoce aleutica			+
Poa alpina	1		1
Poa arctica		1	2
Polygonum viviparrum		+	+
Potentilla diversifolia	1	+	1
Ranunculus eschscholtzi	+		
Salix arctica	4	1	2
Salix reticulata		1	4
Saxifraga cernua		1	
Senecio integrrimus	+		+
Silene acaulis			+
Trollis albiflorous	1		
Veronica alpina	+	1	
Bryophytes		3	
Lichens			2
Bare Soil	+	2	1
Litter	1	1	1
Bare Rock		1	1
LOBE 3			
Androsace septentrionalis			-
Antennaria lanata	-	-	
Antennaria media			-
Astragalus alpinus			-
Carex phaeocephala		-	
Carex rupestris	-		-
Castilleja occidentalis	-	-	
Juncus drummondii	-	-	-
Larix lyallii	-		
Parnaissia fimbrata		-	
Phyllodoce aleutica	-		-
Potentilla diversifolia		-	-
Ranunculus eschscholtzi	-	-	-
Ranunculus pygmaeus		-	-
Salix arctica			-
Salix reticulata			-
Saxifraga lyallii		-	
Senecio integrerrimus	-		-
Sibbaldia procumbens			-

Taraxacum ceriophorum		-	-
LOBE 4			
Antennaria lanata	-		
Arenaria capillaris		-	
Arnica mollis	-	-	
Castilleja miniata	-	-	
Cerastium beeringianum		-	-
Erigeron aureus			-
Luzula spicata		-	
Myosotis sylvatica	-	-	
Pedicularis bracteosa	-	-	-
Poa alpina	-	-	-
Potentialla diversifolia	-	-	
Salix arctica		-	
Senecio integerrimus	-		
Senecio triangularis	-		
Smelowskia calycina		-	
Solidago multiradiata		-	-
Trollis laxus	-		
Vahlodea atropurpurea	-		
Veronica alpina	-		
LOBE 10			
Antennaria media	1		1
Carex nigricans	1		2
Castilleja occidentalis	1	2	
Cerastium beeringianum			+
Draba paysonii			+
Dryas octopetala			1
Erigeron alpinus	+		
Erigeron aureus		+	
Erigeron peregrinus	+		
Fraga glauca			1
Juncus drummondii	2		
Luzula spicata	+		1
Myosotis sylvatica	1		
Oxyria digyma	1	2	
Poa alpina	+	+	1
Poa arctica	+		+
Polygonum viviparum		+	
Potentialla diversifolia	1	+	1
Ranunculus eschscholtzi	+		
Salix arctica	4	1	4
Salix reticulata		4	
Saxifraga rhomboidea	1	2	
Senecio integerrimus	1		+
Silene acaulis	1	+	1
Smelowskia calycina	1		2
Trisetum spicatum			+
Bryophytes	2	2	+
Lichens	1	2	2
Bare Soil	1	2	2
Litter	3		1
LOBE 12			
Antennaria lanata	4	3	4
Antennaria media		1	+
Arnica mollis	1		
Carex nigricans	1		1

Castilleja occidentalis	+		1
Draba paysonii			+
Erigeron aureus			1
Erigeron peregrinus	2	1	2
Festuca ovina		+	
Fragaria virginiana	1	1	
Kobresia myosuroides	3	1	2
Luzula spicata		1	
Myosotis sylvatica		+	
Phleum alpinum	+		
Poa alpina	1		1
Potentialla diversifolia	1	1	+
Ranunculus eschscholtzi	+		
Salix arctica		3	3
Sedum lanceolatum	+		
Selaginella densa			+
Veronica alpina	1		1
Bryophytes	1	2	
Lichen	1	1	
Bare Soil	2	2	1
Litter	2	1	2
Bare Rock		2	

LOBE 13

Anemone parviflora	+	+	
Antennaria lanata			4
Antennaria media	+		+
Carex nigricans			+
Castilleja occidentalis	1		
Cerastium beeringianum			+
Dryas octopetala			2
Erigeron alpinus			1
Erigeron aureus	+		1
Erigeron peregvinus	+		+
Festuca ovina	+	+	
Fragaria virginiana	1		
Gentianella propinquas		+	1
Kobresia myosuroides			1
Luzula spicata	+	+	
Mysostis sylvatica	+		
Oxyria digyma	+	2	
Phyllodoce aleutica	1		1
Poa alpina	2	1	1
Poa arctica			1
Polygonum viviparum	1		+
Potentilla diversifolia	1	1	1
Ranunculus eschscholtzi	+		
Salix arctica	4	2	1
Salix reticulata	1	2	3
Saxifraga rhomboidea	1	1	
Sedum lanceolatum	+	+	+
Selaginella densa	1		
Senecio integerrimus	1	1	
Silene acaulis	2	+	1
Smelowskia calycina	1		2
Veronica alpina	+	+	
Bryophytes	3	3	2
Lichen	2	2	2
Bare Soil	1	1	2
Litter	3		1

Bare Rock		1	2
LOBE 14			
Anemone parviflora	1	2	
Antennaria media	+		+
Carex nigricans	+	+	1
Castilleja occidentalis		1	1
Dryas octopetala		1	2
Erigeron peregrinus	2		
Festuca ovina			+
Fragaria virginiana	+		
Kobresia myosuroides	+		1
Luzula spicata		1	
Myosotis sylvatica	+		
Oxyria digyma	+	2	
Poa alpina	+	+	
Poa arctica			1
Polygonum viviparum		1	1
Potentilla diversifolia	2	2	2
Ranunculus eschscholtzi	+		
Salix arctica	3	3	2
Salix reticulata	1	4	3
Saussurea nuda	+		
Saxifraga oppositifolia			+
Saxifraga rhomboidea	+	+	+
Sedum lancelotum			1
Selaginella densa			1
Senecio integerrimus	1		+
Silene acaulis		+	+
Smelowskia calycina	+	+	1
Bryophytes	3	6	3
Lichen	1	2	1
Bare Soil	1		1
Litter	3	1	1
Bare Rock			2
LOBE 22			
Antennaria lanata	-		-
Arenaria capillaris			-
Carex nigricans	-		
Cassiope tetragona			-
Castilleja occidentalis	-	-	
Dryas octopetala			-
Erigeron aureus	-		-
Juncus drummondii	-	-	
Oxyria digyma		-	
Phyllodoce aleutica		-	
Potentilla diversifolia			-
Salix arctica	-		
Saxifraga lyalli	-	-	
Senecio interrimus			-
Veronica alpina	-	-	-
LOBE 25			
Anemone drummondii	+	+	
Antennaria lanata	+	1	3
Astragalus alpinus	+		1
Castilleja occidentalis	+		1
Equisetum scripoides	+		
Erigeron aureus		+	

Erigeron peregrinus	1	1	
Gentianella propinquas		+	+
Juncus drummondii	+	1	
Luzula spicata	+		
Phyllodoce aleutica	2		2
Poa alpina	1		1
Poa arctica			1
Polygonum viviparum	1	+	1
Potentilla diversifolia	+	+	
Salix arctica	2	2	4
Salix reticulata	4	4	2
Saxifraga lyalli		+	
Senecio integerrimus	+	1	1
Silene acaulis	+		
Solidago multiradiata		1	
Taraxacum certophorum	+		
Veronica alpina	+	+	
Bryophytes	1	3	2
Lichen	1	1	1
Bare Soil	1	2	1
Litter	2	1	1
Bare Rock	1	1	1
LOBE 28			
Agoseris glauca			-
Antennaria lanata	-	-	-
Arenaria capillaris			-
Arnica mollis	-	-	-
Carex nigricans	-	-	
Castilleja occidentalis	-		
Dryas ocopetala			-
Erigeron aureus			-
Juncus drummondii			-
Luzula spicata		-	
Myosotis sylvatica	-	-	
Oxyria digyma	-	-	
Pedicularis bracteosa	-		-
Phleum alpinum	-	-	
Poa alpina			-
Potentilla diversifolia		-	-
Salix arctica			-
Vahlodea atropurpurea	-		
Valeriana sitchensis	-	-	
Veronica alpina		-	-
LOBE 34			
Achillia millefolium	1	1	1
Antennaria lanata		+	
Antennaria media	1		
Arenaria capillaris	+	+	+
Arnica mollis	1	1	
Carex nigricans	1	+	2
Castilleja occidentalis			+
Epilobium angustifolium	+	+	
Erigeron peregrinus	2	2	
Fragaria virginiana	1	1	
Kobresia myosuroides	1	2	2
Luzula spicata			+
Penstemon ssp.			1
Phleum alpinum	1	+	1
Phyllodoce aleutica			2
Poa arctica		1	

Potentilla diversifolia	1	1	2
Selaginella densa		2	2
Trisetum spicatum	1		1
Vaccinium scoparium	3	3	2
Veronica alpina		1	1
Lichens	1	1	1
Bare Soil	+	2	1
Litter	2	2	2
LOBE 35			
Antennaria lanata	2	3	
Arnica mollis	1		
Carex nigricans	1	+	
Castilleja occidentalis			1
Erigeron peregrinus	2	+	1
Festuca ovina			+
Fragaria virginiana	1		1
Kobresia myosuroides	2	2	3
Luzula spicata		+	
Phleum alpinum	1		
Phyllodoce aleutica	2		1
Poa arctica		1	
Potentilla diversifolia	+	+	1
Selaginella densa	+	2	2
Trisetum spicatum	1		
Vaccinium scoparium	3	3	2
Veronica alpina	+	1	
Bryophytes	+	+	+
Lichen		2	
Bare Soil	1	1	1
Litter	2	2	2
LOBE 37			
Achillia millefolium	+		
Arenaria capillaris			+
Astragalus alpinus			+
Carex nigricans			+
Cerastium beeringianum			+
Draba oligosperma	+	1	
Dryas ocopetala	2		2
Erigeron aureus	+		
Erigeron peregrinus	2	1	1
Festuca ovina	+	+	
Luzula spicata		1	+
Myosotis sylvatica		+	
Phyllodoce aleutica	1		
Poa alpina	1	1	
Poa arctica	1		1
Polygonum viviparum			+
Potentilla diversifolia	1	1	1
Salix arctica	2		
Saxifraga adscendens		+	+
Senecio integerrimus		1	
Silene acaulis			1
Smelowskia calycina	+	1	1
Solidago multiradiata	1		
Trisetum spicatum		1	
Bryophytes	2	6	4

Lichen		+	
Bare Soil	1	+	+
Litter	2	2	1
Bare Rock	1		
LOBE 38			
Achillia millefolium	1	1	1
Astragulus alpinus	3	4	1
Carex nigricans			+
Cerastium beeringianum	+		
Draba oligosperma		+	
Dryas ocopetala			3
Erigeron aureus	+		
Erigeron peregrinus	1		
Erigeron purpurateus	+		
Hedysarum sulphurescens	1		
Luzula spicata	+		
Myosotis sylvatica	+		
Poa alpina	1	1	1
Poa arctica	1		
Polygonum viviparum			+
Potentilla diversifolia	1		1
Potentilla hyparctica			+
Salix arctica	4	2	2
Salix reticulata	3	2	2
Senecio integerrimus	1		+
Smelowskia calycina	+	1	1
Solodago multiradiata	1	1	1
Trisetum spicatum	+		+
Veronica alpina	+		
Bryophytes		2	2
Lichen		1	1
Bare Soil	1		1
Litter	2		1

Appendix VI : Vegetation Structure by Quadrat

1 : SPECIES STRUCTURE OF QUADRAT A (LOBE FRONT)

Species	% cover	% quadrat frequency	prominence value (PV)
Salix arctica	28.6	57	216.20
Antennaria lanata	15.0	43	98.20
Vaccinium scoparium	23.0	13	83.98
Juncus drummondii	11.7	33	67.55
Salix reticulata	14.7	21	67.36
Kobresia myosuroides	10.5	29	56.13
Arnica mollis	8.5	36	50.80
Phyllodoce aleutica	8.0	36	47.81
Dryas octopetala	15.0	7	40.09
Astralagus alpinus	10.0	14	37.80
Potentilla diversifolia	2.5	86	23.15
Silene acaulis	4.0	21	18.52
Poa alpina	2.3	57	17.39
Fragaria virginiana	2.2	36	13.15
Carex nigricans	1.6	50	11.31
Achillia millefolium	2.4	21	11.11
Trisetum spicatum	2.4	21	11.10
Phleum alpinum	2.0	29	10.69
Senecio integerrimus	1.5	50	10.61
Saxifraga rhomboidea	2.0	21	9.26
Smelowskia calycina	1.5	36	8.96
Oxyria digyma	1.7	27	8.83
Taraxacum certophorum	3.0	7	7.94
Castilleja occidentalis	1.1	50	7.78
Veronica alpina	1.0	57	7.71
Myosotis sylvatica	1.1	36	6.57
Poa artica	1.4	21	6.48
Polygonum viviparum	1.4	21	6.48
Luzula spicata	0.9	36	5.38
Trollis albiflorous	2.0	7	5.29
Selaginella densa	1.1	14	4.16
Anemone parviflora	0.9	14	3.40
Hedysarum sulphurecens	1.0	7	2.65
Ranunculus eschscholtzi	T	43	0.66
Erigeron aureus	T	36	0.59
Antennaria media	T	21	0.46
Festuca ovina	T	14	0.38
Anemone drummondii	T	7	0.27
Arenaria capillaris	T	7	0.27
Draba oligosperma	T	7	0.27
Epilobium angustifolium	T	7	0.27
Equisetum scipoides	T	7	0.27
Erigeron alpinus	T	7	0.27
Erigeron purpuratus	T	7	0.27
Saussura nuda	T	7	0.27
Carex phaeocephla		14	
Deschampsia atropurpurea		14	
Arabis lyallii		7	
Carex rupestris		7	
Castilleja miniata		7	
Cerastium berringianum		7	
Pedicularis bracteosa		7	
Saxifraga lyalli		7	
Senecio triangularis		7	
Taraxacum ceratophorum		7	
Trollis laxus		7	
Valeriana sitchensis		7	
Lichens	1.9	100	19.00
Mosses	5.3	100	53.00

2 : SPECIES STRUCTURE OF QUADRAT B (LOBE RISER)

Species	% cover	% quadrat frequncy	prominence value (PV)
Salix reticulata	23.7	43	155.21
Astragalus alpinus	30.0	7	79.37
Vaccinium scoparium	17.5	14	65.48
Oxyria digyma	10.3	36	62.00
Salix arctica	11.0	57	60.40
Antennaria lanata	8.2	36	49.20
Kobresia myosuroides	10.0	21	45.83
Selaginella densa	10.0	14	37.42
Arnica mollis	6.0	14	22.45
Potentilla diversifolia	2.4	79	21.10
Saxifraga rhomboidea	4.0	21	18.47
Castilleja occidentalis	4.0	21	18.33
Erigeron peregrinus	3.0	36	15.40
Juncus drummondii	2.5	36	15.00
Achillia millefolium	2.3	36	14.00
Smelowskia calycina	2.4	29	12.74
Poa arctica	2.6	21	12.20
Anemone parviflora	3.0	14	11.23
Luzula spicata	2.5	36	11.07
Anemone drummondii	2.5	14	9.54
Dryas ocopetala	3.5	14	9.26
Solidago multiradiata	2.0	21	9.17
Erigeron aureus	1.7	21	7.94
Senecio integerrimus	1.7	21	7.65
Fragria virginiana	1.7	21	7.64
Poa alpina	1.1	36	6.30
Draba oligosperma	1.6	14	5.80
Veronica alpina	0.8	43	5.51
Antennaria media	1.0	14	3.74
Polygonum vivipaum	0.6	29	3.10
Saxifraga cunua	1.0	7	2.65
Carex nigricans	0.3	36	1.80
Cerastium beeringianum	T	43	0.66
Myosotis sylvatica	T	36	0.60
Festuca ovina	T	21	0.46
Saxifraga lyalli	T	21	0.46
Silene acaulis	T	21	0.46
Gentianella propinquas	T	14	0.37
Phleum alpinum	T	14	0.37
Ranumculus eschscholtzi	T	14	0.37
Arnica mollis	T	7	0.27
Draba fladnizensis	T	7	0.27
Epilobium angustifolium	T	7	0.27
Equisetum scripoides	T	7	0.27
Erigeron alpinus	T	7	0.27
Saxifraga adscendens	T	7	0.27
Sedum lanceolatum	T	7	0.27
Trisetum spicatum	T	7	0.27
Agoseris glauca		7	
Androsace septentrionalis		7	
Carex phaeocephala		7	
Castilleja miniata		7	
Parnaissa miniata		7	
Pedicularis braceteosa		7	
Phyllodoce aleutica		7	
Ranunculus pygmaeus		7	
Taraxacum certophorum		7	
Valeriana sitchensis		7	
Lichen	3.9	100	38.50
Moss	10.9	100	109.00

3 : SPECIES STRUCTURE OF QUADRAT C (LOBE TREAD)

Species	% cover	% quadrat frequency	prominence value (PV)
Salix reticulata	28.0	43	183.61
Salix arctica	19.6	71	165.36
Antennaria lanata	19.3	36	116.00
Phyllodoce aleutica	16.0	29	86.16
Dryas octopetala	11.6	43	76.07
Kobresia myosuroides	10.0	36	60.00
Vaccinium scoparium	11.0	14	41.16
Potentilla diversifolia	3.9	79	34.57
Smelowskia calycina	5.0	36	30.00
Selaginella densa	5.5	29	29.78
Erigeron peregrinus	3.7	43	24.26
Poa arctica	3.2	43	20.77
Carex nigricans	2.6	57	19.55
Poa alpina	1.8	57	13.82
Solidago multiradiata	3.0	21	13.75
Silene acaulis	1.8	36	11.04
Castilleja occidentalis	1.4	50	10.04
Achillia millefolium	2.0	21	9.32
Astragalus alpinus	1.6	29	8.35
Fragaria viriniana	3.0	7	7.94
Potentilla hyperarctica	1.6	14	5.80
Polygonum viviparum	0.9	43	5.79
Antennaria media	0.8	50	5.66
Trisetum spicatum	1.1	7	5.65
Senecio interrimus	0.7	57	5.51
Veronica alpina	1.0	29	5.39
Phleum alpinum	2.0	7	5.29
Erigeron alpinus	1.0	21	4.58
Fragaria glauca	1.0	7	2.65
Sedum lanceolatum	0.6	14	2.06
Gentianella propinquas	0.4	21	1.83
Luzula spicata	0.4	21	1.83
Arenaria capillaris	T	21	0.46
Festuca ovina	T	21	0.46
Arnica mollis	T	14	0.37
Cerastium beeringianum	T	14	0.37
Draba paysonii	T	14	0.37
Oxytropis podocarpa	T	14	0.37
Equisetum scripoides	T	7	0.26
Juncus drummondii	T	7	0.26
Myosotis sylvatica	T	7	0.26
Oxyria digyma	T	7	0.26
Saxifraga adscendens	T	7	0.26
Saxifraga oppositifolia	T	7	0.26
Saxifraga rhomboidea	T	7	0.26
Agoseris glauca		7	
Androsace septentrionalis		7	
Carex phaeophala		7	
Carex rupestris		7	
Cassiope tetragona		7	
Pedicularis bracteosa		7	
Ranunculis eschscholtzi		7	
Sibbaldia procumbens		7	
Taraxacum ceratophorum		7	
Lichen	3.9	78	33.74
Moss	2.90	78	81.25